Sandia National Laboratories
Operated for the U.S. Department of Energy by
Sandia Corporation

Les E. Shephard
Director, Geoscience & Environment Center

P.O. Box 5800
Albuquerque, NM 87185-0701

Phone: (505) 845-9738
Fax: (505) 844-0591
Internet: lesheph@sandia.gov

Mr. Michael J. Zamorski
Area Manager
Kirtland Area Office
Department of Energy
P.O. Box 5400
Albuquerque, New Mexico 87115

SEP 23 1999

Dear Mr. Zamorski:

Subject: Transmittal of Site-Wide Hydrogeologic Characterization Project 1995 Annual Report (Revised February 1998)

Please find enclosed for transmittal copies to the Environmental Protection Agency. This report is intended to be the final pending its approval and a permit modification. If there are any questions, you can reach Sue Collins of my staff at 284-2546.

Sincerely,

LEShepherd

Enclosures:

Copy to (w/o attachments):
MS 0184 John Cromier, DOE/KAO
MS 0184 John Gould, DOE/KAO
MS 0184 Beth Oms, DOE/KAO

Copy to (w/o attachments):
MS 1087 Sue Collins, 6133
MS 1087 Fran Nimick, 6133
MS 1089 Warren Cox, 6132
MS 1089 M. J. Davis, 7571
MS 1089 Dick Fate, 6135

Copy to (w/attachment):
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Sandia National Laboratories

Site-Wide Hydrogeologic Characterization Project

1995 Annual Report
Revised February 1998

Environmental
Restoration
Project

United States Department of Energy
Albuquerque Operations Office

SITE-WIDE HYDROGEOLOGIC CHARACTERIZATION PROJECT

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SANDIA NATIONAL LABORATORIES
SITE-WIDE HYDROGEOLOGIC CHARACTERIZATION PROJECT
1995 ANNUAL REPORT
REVISED FEBRUARY 1998

Contributors/Authors

Bayliss, Linda S. (SNL/NM)
Burck, Peter W. (INTERA, Inc.)
Collins, Sue (SNL/NM)
Duval, Tom (INTERA, Inc.)
Foutz, Walt (Lamb Associates, Inc.)
Haggerty, Grace (GRAM, Inc.)
McCord, James T. (SNL/NM)
McCord, John P. (INTERA, Inc.)
Storms, Erik (INTERA, Inc.)
Thomas, Erich C. (GRAM, Inc.)
Van Hart, Dirk (GRAM, Inc.)
Wolford, Ross (GRAM, Inc.)

The general point of contact for this report is Sue Collins (SNL/NM),Task Leader for the Site-Wide Hydrogeologic Characterization Project.

Acknowledgments

Linda Bayliss, The Environmental Restoration Geographical Information System, Sandy McKay, Sharon O'Connor, Shari Lewis, Brenda Bailey-White.

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EXECUTIVE SUMMARY

This report was prepared by the Site-Wide Hydrogeologic Characterization Project of the Environmental Restoration Project at Sandia National Laboratories, New Mexico, for calendar year 1995. This report also includes revisions suggested by the New Mexico Environment Department's Department of Energy Oversight Bureau and draft Environmental Protection Agency comments issued in 1996. This work was supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

This report satisfies the requirements of Section C.2 in Module IV, Special Conditions Pursuant to the 1984 Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act for Sandia National Laboratories, New Mexico, I.D. NM5890110518, of the Resource Conservation and Recovery Act Part B Hazardous Waste Facility Permit issued to the U.S. Department of Energy and Sandia National Laboratories, New Mexico as co-permittees (EPA 1993). Preparation of this report is required by Section IV. C. of the Permit, which directs the permittee to submit a report that describes the current knowledge of the installation-wide hydrogeological environment. The Site-Wide Hydrogeologic Characterization Project has substantially added to the available knowledge about the aquifer beneath Sandia National Laboratories, New Mexico and Kirtland Air Force Base.

Sandia National Laboratories, New Mexico and Kirtland Air Force Base lie on the edge of the Rio Grande Valley. The most prominent hydrologic feature is Tijeras Arroyo, which drains approximately 120 square miles that include most of Sandia National Laboratories, New Mexico and Kirtland Air Force Base. The channels of the Rio Grande and Tijeras Arroyo have moved substantially over time in this complex geological area. Elevations range from approximately 7700 feet in the east to 5200 feet in the west. The bedrock surface comprises the mountain tops in the east and is buried by more than 1000 feet of sediments in the west. Several faults divide the bedrock surface into numerous blocks. The tops of many of the fault blocks are back-tilted toward the east. The particle size of materials comprising sediments varies widely from point to point, but two main groups of materials can be identified. The Ancestral Rio Grande deposited relatively uniform materials with high hydraulic conductivities along the western portions of Sandia National Laboratories, New Mexico and Kirtland Air Force Base. East of this, most materials were deposited as alluvial fans from the mountains; these materials are typically less well sorted and have lower hydraulic conductivities. The boundary between these two general areas is composed of overlapping fingers of each material and thus is not well defined.

Average annual precipitation for this area is approximately 12 inches, ranging from about 8 inches at the airport to about 20 inches at the eastern mountain tops. Less than 1% of this rainfall leaves Sandia National Laboratories, New Mexico and Kirtland Air Force Base as streamflow; the vast majority of rainfall is evapotranspired. Surface water quality data suggest that little or no contamination is transported by streamflow either on-site or from the area.

Recharge to the aquifer from concentrated flows in larger arroyos is estimated as a few feet per year within the active channel. Smaller arroyos do not appear to be a source of aquifer recharge at points distant from the mountains. Recharge from the mountain tops and mountain fronts appears to be approximately the same order of magnitude as the volume of recharge from larger arroyos. Data available to date suggest the total annual aquifer recharge on Sandia National Laboratories, New Mexico and Kirtland Air Force Base approximates the annual water use of about 1000 people using

250 gallons per person per day (approximately 12 million cubic feet). Additional, perhaps greater, aquifer recharge may enter the area from subsurface flows from the Tijeras Arroyo canyon area upstream of Sandia National Laboratories, New Mexico and Kirtland Air Force Base.

Unsaturated material between the ground surface and the water table, the vadose zone, varies from approximately 500 feet thick in the west to zero (at springs) in the east. Vadose zones in the eastern plains are typically 50 to 100 feet thick. The vadose zone is important in estimating contaminant transport times because of its thickness and very low to nonexistent recharge rates (where concentrated water is absent). For example, the largest estimate of local recharge through the vadose zone obtained by chloride mass balance techniques was about 0.5 millimeter per year, which corresponds to a flow velocity of about 1 centimeter per year at typical (5% by volume) upland soil water contents. If any contamination existed when Sandia National Laboratories was established, the vertical, dissolved-phase movement of that contamination in upland areas has been less than a few feet to date. Recharge is arguably zero outside areas with concentrated runoff or human interference. Significant movement of water through the vadose zone requires a concentrated, frequent, or large water supply. Such sources may include some arroyos, excavations within otherwise nonrecharging arroyos, artificial ponds, drain fields, or leaky pipes and sewers. Whether such flows reach the water table depends on the total volume of water available, the characteristics of the vadose zone and the input rate that determine the volume of soil materials affected, the incremental ability of those soils to store additional water and time.

The saturated zone includes the regional aquifer and any saturated, perched aquifers above it. Head and hydraulic conductivity measurements from numerous wells, chemical analysis of water from wells and springs, and geology/geophysical work provide saturated zone information. Generally, water flows westward from the mountains toward the Rio Grande, where the groundwater historically added to the flow of the river. Withdrawals of water by City of Albuquerque and Kirtland Air Force Base wells has changed the direction of this flow in recent years, so that water from the river now flows toward a trough in the aquifer heads just west of Technical Area III on Sandia National Laboratories, New Mexico and Kirtland Air Force Base. Indications are that this trough is a high permeability pathway, which may be related to ancestral Rio Grande sediment deposits. It is also possible that this is a buried, ancestral Tijeras Arroyo channel.

Saturated groundwater flow in the canyons area of Arroyo del Coyote occurs primarily in confined, fractured rock aquifers, occasionally rising to the surface at springs. Flow occurs in both confined and unconfined aquifers in the Hubbel Bench area to the south of Arroyo del Coyote, where the depth to water (or to where water rises within a well) is typically less than 200 feet below the ground surface. West of the fault complex, the water surface in wells is typically 500 feet below ground surface, in the deep, regional aquifer. Most wells in the regional aquifer show some decline in water levels due to pumping from the water supply wells to the north. Water level declines range from about 0.5 feet per year near the faults, to 3 or more feet per year beneath northwestern portions of Kirtland Air Force Base. The rate of decline of water level at a particular well is affected by the depth at which it is completed. For example, data from some areas within Technical Area III suggest that water supply wells extract a disproportionate amount of water from deeper portions of the aquifer. This leads to a more rapid head decline in deep wells, while heads in less permeable, upper aquifer layers decline more slowly as vertical flows chase the declining water levels below. There is no indication that drawdowns caused by pumping wells extend eastward across the faults.

Flows in the southern portions of the regional aquifer are typically toward the west-northwest, until they intersect the trough in the groundwater profile along the western edge of Technical Area III. In this region, flows turn toward the water supply wells to the north.

The perched water zone near where Tijeras Arroyo enters Kirtland Air Force Base covers an area of about 2 square miles, from the southern portion of Technical Area I to the Tijeras Arroyo Golf Course, with Tijeras Arroyo passing just east of its center. If this is a continuous feature across its mapped area, gradients indicate the flow is from northwest of Technical Area IV toward the Tijeras Arroyo Golf Course. The highest heads in this perched zone are northwest of Tijeras Arroyo, and the flow appears to be across Tijeras Arroyo toward the southeast, rather than away from the arroyo. It is suspected that the water source for this feature is a buried, ancestral channel of Tijeras Arroyo, which is supplied by subsurface flow from areas outside of Sandia National Laboratories, New Mexico and Kirtland Air Force Base.

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GLOSSARY

acre-foot - The volume of water, 43,560 cubic feet, that will cover an area of 1 acre to a depth of 1 foot.

alluvial - Deposited by flowing water.

alluvial fan - A low, cone-shaped deposit of alluvium made by a stream, generally issuing from mountainous constrictions (gorges) out onto a level plain.

alluvium - An unconsolidated terrestrial sediment composed of sand, gravel, and clay that has been deposited by water.

anastomosing - Branching and recombining, as in a network of subparallel faults.

ancestral - Qualification used to refer to a geologic feature at some earlier geologic time.

antithetic fault - A minor normal fault that is oriented opposite to the major fault with which it is associated.

arkosic - Qualification used in reference to coarser-grained sedimentary rocks, indicating a 25% or greater feldspar content.

arroyo - A steep-sided and flat-bottomed gully in an arid region that is occupied by a stream only intermittently, after rains.

ash - Fine, airborne volcanic material, spread over wide geographic areas during eruption events.

bajada - A broad, continuous alluvial slope or gently inclined surface extending along and from the base of a mountain range, out into and around an inland basin.

basement complex - All-inclusive term used to reference consolidated rocks underlying sedimentary rocks under investigation; top surface generally is an erosional surface.

basin - A geographically extensive depressed area into which the adjacent land drains, having few or no surface outlets.

bedrock - A general term for the rock, usually solid, that underlies soil or other unconsolidated, surface material.

biotite - A mica mineral that is rich in iron and magnesium.

biotite granite - A form of granite that contains 10% or more biotite.

buried soil - A previously formed soil that has been covered by more recent sediments.

calcarenite - A deposit composed of cemented sand-size grains of calcium carbonate.

GLOSSARY (Continued)

calcareous - Containing calcium carbonate.

caldera - A large basin-shaped volcanic depression that is roughly circular in shape.

carbonaceous - A deposit that is coaly.

carbonate - A sediment formed by precipitation from solution of carbonates of calcium, magnesium, or iron.

Cenozoic - A geologic time era (refer to the Geologic Time Scale figure at the end of the glossary).

chert - A silica-rich sedimentary rock.

clastic - Consisting of fragments of rocks or organic structures that have been moved individually from their place of origin.

clay - A rock or mineral particle having a diameter less than 0.002 mm.

claystone - A hard clay.

closed depression - An area of lower ground indicated on a topographic map by a closed, hachured contour line.

coalescent - Indicating a series of alluvial fans and/or piedmont alluvium that join to produce a continuous pediment or bajada.

coarse-grained - A descriptor of sedimentary deposits, and of its texture, in which the individual grains have an average diameter greater than 2 mm.

colluvium - Loose and incoherent sedimentary deposits usually at the foot of a slope or cliff, resulting from unconfined wash and hillslope erosion of soil and rock.

conglomerate - A cemented sedimentary rock containing rounded fragments corresponding in their grade sizes to gravel or pebbles.

Cretaceous - A period in the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

cross-bedded - Arrangement of strata laminations transverse or oblique to the main bedding plain of the strata of concern.

debris-flow - A general designation for all types of deposits resulting from rapid flow, involving rock material derived from the erosion and disintegration of rocks.

depo center - An area of maximum deposition.

GLOSSARY (Continued)

deposit - A layer of sediments left by water, wind, or ice.

diagenesis - All of the physical and chemical changes undergone by a sediment after its initial deposition, exclusive of weathering and metamorphism.

dip - The angle at which strata are inclined from horizontal; it is measured perpendicular to the strike.

drainage basin - The many tributaries which define a network of channels that drain to a discernible, finite area.

embayment - Similar to a basin of sedimentation, but generally is not totally surrounded by elevated areas.

en echelon - Descriptive of geologic features that are in an overlapping or staggered arrangement, e.g., faults.

Eocene - An epoch in the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

eolian - Refers to deposits transported and arranged by the wind (e.g., eolian dunes).

ephemeral drainage - A stream or reach of a stream that flows briefly in response to precipitation in the immediate vicinity, whose channel is at all times above the water table.

ephemeral stream - One that flows only for a short duration during and following rainfall or snowmelt.

escarpment - A long, continuous cliff or steep slope facing in one general direction, which breaks the general continuity of the land by separating two level or gently sloping surfaces, and is produced by erosion or faulting.

facet - A plane surface produced by faulting, and intersecting the general slope of the land.

fan - A sediment deposit in the shape of a fan, generally formed upon exiting a confined mountain valley into an open plain.

fanglomerate - Composed of heterogeneous materials originally deposited in an alluvial fan and subsequently cemented into solid rock.

fault - A planar or gently curved fracture in the earth's crust across which there has been relative displacement.

fault zone - A wide zone of relative displacement as opposed to a single clean fracture.

fault-hachure - A map notation of short barbs on one side of a fault trace, indicating which side of the fault was displaced downward relative to the other side.

GLOSSARY (Continued)

feldspar - The most abundant mineral on earth, constituting 60% of the earth's crust.

floodplain - That portion of the river valley adjacent to the river channel, which is built of generally unconsolidated sediment, deposited at times of river flood.

fluvial - Of, or pertaining to, rivers.

fluvial deposit - A sedimentary deposit consisting of material transported by, suspended in, or laid down by a river stream.

formation - The primary stratigraphic unit which can be mapped or described.

fractures - Breaks in rocks due to intense folding or faulting.

geochemistry - The interaction of water, minerals, and organic materials in the soil.

geomorphic - Pertaining to the form of the earth or of its surface features.

geomorphic province - A large area or region considered as a whole, all parts of which are characterized by similar geomorphic features, differing from those of adjacent areas.

geomorphic subprovince - A subset of a geomorphic province.

geomorphology - The branch of geology which deals with the form of the earth, the general configuration of its surface, and the changes that take place in the evolution of landforms.

gneiss - Coarse-grained, banded metamorphic rock.

graben - A block, generally long compared to its width, that has been downthrown along faults relative to rocks on either side.

granite - A coarse-grained igneous rock consisting mainly of quartz and feldspar minerals.

gravel - The coarsest of alluvial sediments, consisting of rounded rock and mineral pieces larger than 2 mm, including cobbles and boulders.

greenstone - Altered igneous rocks which owe their color to the presence of chlorite and other green-colored minerals.

group - A stratigraphic unit consisting of two or more formations.

gypsum - A calcium sulfate mineral commonly associated with evaporite settings.

hachure - One of the short lines used to shade, or to indicate slopes on maps, and also their degree and direction.

GLOSSARY (Continued)

half-graben - A depressed block bounded on one side by a fault.

hogback - A ridge produced by highly-tilted strata.

Holocene - An epoch of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

horst - A block of the earth's crust, generally long compared to its width, that is uplifted along faults relative to rocks on either side.

hydraulic conductivity - The rate at which a unit cross-sectional area of soil will transmit water under a unit hydraulic gradient.

hydrology - The science that relates to the water of the earth.

igneous - A rock formed by solidification from a molten or partially molten state.

indurated - Descriptive of a rock or soil hardened or consolidated by pressure, cementation, or heat.

interfluve - A relatively undissected upland between adjacent streams flowing in the same general direction.

infiltration - The process of water passing through the surface of the soil through joints and pores; this water does not necessarily (and, in most cases, mostly does not) recharge the aquifer beneath it, due to evaporation.

inset terrace - A stream terrace formed during successive periods of vertical and lateral erosion, leaving remnants of former valley walls on both sides of the valley.

intermittent stream or spring - One that does not flow year-round.

interstratified - Descriptive of strata layered between, or alternating with, other strata.

isopach - Map contour line that indicates a lithologic unit of equal thickness.

landform - Any physical, recognizable form or feature of the earth's surface, having a characteristic shape, and produced by natural causes.

limestone - A bedded, sedimentary deposit consisting chiefly of calcium carbonate, usually as the mineral calcite.

lineament - Straight or gently curved, lengthy features of the earth's crust, frequently expressed as lines of depression.

lithology - The systematic description of rocks, in terms of mineral composition and texture, usually as observed by the eye.

GLOSSARY (Continued)

loam - A rich, permeable soil, composed of equal or moderate proportions of clay, silt, and sand, and usually containing organic matter.

mafic - Descriptive of igneous rock composed chiefly of dark, ferromagnesian minerals.

marine - Of, belonging to, or caused by the sea.

matrix - In a rock in which certain grains are much larger than the others, the grains of the smaller size comprise the matrix.

Mesozoic - An era of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

metaigneous - Igneous rocks which have undergone change due to high temperatures and pressures within the earth.

metamorphic - Those rocks formed in the solid state, whose original mineralogy, texture, or composition has been changed in response to pronounced changes of temperature, pressure, and chemical environment.

metarhyolite - A volcanic rock that has undergone change due to high temperature and pressure.

metasedimentary - A sedimentary rock that has undergone change due to high temperature and pressure.

micaceous - Rocks that contain abundant mica mineral flakes.

microcline - A potassium-rich feldspar mineral commonly found in granites.

Miocene - An epoch of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

Mississippian - A period of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

mudstone - A rock that includes clay, silt, siltstone, claystone, shale, and argillite.

neutron access tube - A pipe emplaced in the ground (usually vertically) for purposes of passing a neutron probe through it, to measure soil water content at various depths or locations.

GLOSSARY (Continued)

neutron probe - A device commonly in use since the 1950s, that emits high-energy neutrons, and counts low-energy neutrons in a spherical zone around the probe; more measured low-energy neutrons indicate that high-energy neutrons lost their energy by colliding with hydrogen atoms, normally indicating the amount of water present in that area.

nonmarine - Of, belonging to, or caused by conditions outside of the sea environment.

normal fault - A fault where the upper surface moved down relative to the lower surface.

Oligocene - An epoch of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

oolitic - Consisting of spherical to ellipsoidal bodies (0.25 to 2.00 mm) which have formed through concentric growth, often by accretion.

organic matter - Formed by decay of once-living material.

outcrop - A segment of bedrock exposed above the ground surface.

overbank - A floodplain deposit.

Paleocene - An epoch of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

Paleozoic - An era of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

pediment - A planar, erosional, sloping rock surface forming a ramp up to the front of a mountain range in an arid region, which is carved in bedrock with a thin veneer of fluvial gravel.

Pennsylvanian - A period of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

percolating water - Water that oozes, seeps, or filters through the soil without a definite channel.

perennial stream or spring - A stream or spring that flows all year.

permeability - The property or capacity of a porous rock, sediment, or soil for transmitting a fluid without impairment of the structure.

Permian - A period of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

piedmont - A sloped surface lying or formed at the base of a mountain, which connects the mountain to the level of adjacent plains.

GLOSSARY (Continued)

platform - The area of thinner sediments adjoining areas of thick sediment wedges.

playa-lake - Broad, shallow sheets of water that quickly gather and almost as quickly evaporate.

Pleistocene - An epoch of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

Precambrian - The time period preceding the Cambrian (refer to the Geologic Time Scale figure at the end of the glossary).

quartz - A mineral consisting of silicon dioxide.

quartzite - A metamorphic rock consisting mainly of quartz.

Quaternary - A period of the geologic time scale (refer to the Geologic Time Scale figure at the end of the glossary).

Recent - Equivalent to the Holocene.

recharge - Water reaching the water table or aquifer.

relay fault - A fault subparallel to adjoining faults, that is configured in a side-step fashion, which assumes the motion to the adjoining faults.

relict - A residual topographic feature.

relief - The maximum regional difference in elevation.

residuum (residue) - An accumulation of rock debris formed by weathering and remaining essentially in place after all but the least soluble constituents have been removed, usually forming a comparatively thin surface layer concealing the bedrock below.

rift - A large strike-slip fault parallel to the regional geologic structure.

sand - A rock or mineral particle having a diameter from 0.05 to 2 mm.

sandstone - A sedimentary rock composed of grains from 0.05 to 2 mm in diameter, cemented together by silica, carbonate, or other minerals, or a clay matrix.

scarp - A cliff or steep slope of some geographic extent along the margin of a plateau, mesa, or terrace.

schist - A medium- to coarse-grained metamorphic rock with subparallel orientation of the mica minerals.

GLOSSARY (Continued)

sediment - Solid fragments, that originate from the weathering of rocks and are transported by, suspended in, or deposited by, air, water, or ice.

sedimentary rock - A rock formed by the accumulation and cementation of mineral grains transported by wind, water, or ice to the site of deposition, or chemically precipitated at the depositional site.

shale - A laminated, fissile and indurated sedimentary rock with a predominance of clay minerals.

silt - A rock or mineral particle having a diameter from 0.002 to 0.05 mm.

siltstone - A very fine-grained consolidated sedimentary rock, with at least two-thirds of its material of silt size.

soil - A natural body consisting of layers or horizons of mineral and/or organic constituents with variable thicknesses, which differ from the parent material (the unconsolidated material from which soil develops).

soil horizon - A layer of soil that is distinguishable from adjacent layers by characteristic physical properties such as structure, color, or texture.

soil survey - The systematic examination of soils in the field and in the laboratory, including their description, and classification.

sorb - To absorb and/or adsorb.

strata - A series of single sedimentary beds or layers, regardless of thickness.

stratigraphy - That branch of geology which deals with the formation, composition, sequence, and correlation of stratified rocks.

strike - The course or bearing of the outcrop of an inclined bed or structure on a level surface.

strike-slip fault - A fault with net slip nearly in the direction of fault strike.

structural bench - A bench representing the resistant edge of a structural terrace which is being reduced by erosion.

structural geology - The study of the structural features of rocks, and the geographic distribution of features, and their causes.

subcrop - Rocks occurring under a defined overlying unit, separated by an unconformity.

subparallel - Adjective referring to "nearly" parallel.

GLOSSARY (Concluded)

surface (sheet) erosion - An erosion in which thin layers of surface material are gradually removed more or less evenly, by broad continuous sheets of running water, rather than streams in well defined channels.

surface water - Water that moves along the surface in the form of a thin, continuous film, which is not concentrated in large channels, and is a result of heavy rainfall in arid regions.

surficial deposit - Unconsolidated and residual, alluvial, or glacial deposits lying on bedrock, representing the most recent of geologic deposits.

synthetic fault - A minor normal fault which has the same orientation as the major fault with which it is associated.

tectonism - Earth's crustal instability.

terrace - A relatively flat, horizontal, gently inclined surface, sometimes long and narrow, which is bounded by a steeper ascending slope on one side, and a steeper descending slope on the opposite side.

trend - The direction or bearing of an outcrop of a geological feature, such as a layer or escarpment.

tributaries - Streams feeding, joining, or flowing into a larger stream or a lake.

unconformity - A surface of erosion that separates younger strata from older strata.

uplift - Elevation of any extensive part of the earth's surface relative to some other parts.

valley floor - The comparatively broad and flat bottom of a valley.

vertical exaggeration - The resulting visual discrepancy when using a larger vertical scale than horizontal scale in the construction of geologic cross sections.

water year - The period from October 1 through the following September 30; often chosen for surface hydrology measurements because of typically minimal runoff events near the end of September in many locales in North America.

watershed area - The area upstream of a given point on a stream channel, all flows from which will pass by that point unless they infiltrate or evaporate.

weathering - The set of all processes that decay and break up bedrock, by a combination of physical fracturing and/or chemical decomposition.

GEOLOGIC TIME SCALE

ERA	PERIOD	EPOCH	Millions of Years* Duration	Millions of Years* Before Present
CENOZOIC	Quaternary	Holocene	.01	
		Pleistocene	1.8	1.8
	Tertiary	Pliocene	3.2	
		Miocene	19	
		Oligocene	13	
		Eocene	21	
		Paleocene	7	65
MESOZOIC	Cretaceous		79	144
	Jurassic		69	213
	Triassic		35	248
PALEOZOIC	Permian		38	286
	Pennsylvanian		34	320
	Mississippian		40	360
	Devonian		48	408
	Silurian		30	438
	Ordovician		67	505
	Cambrian		85	590
PRECAMBRIAN				

*Source: Stanley, S.M., 1986. Earth and Life through Time, 3rd Ed.; W.H. Freeman and Co., NY.

METRIC/ENGLISH CONVERSION TABLE

Hydraulic conductivity (*K*)			
Meters per day ($m\ d^{-1}$)	Centimeters per second ($mc\ s^{-1}$)	Feet per day ($ft\ d^{-1}$)	Gallons per day per square foot ($gal.\ d^{-1}\ ft^{-2}$)
1	1.16×10^{-3}	3.28	2.45×10^{1}
8.64×10^{2}	1	2.83×10^{3}	2.12×10^{4}
3.05×10^{-1}	3.53×10^{-4}	1	7.48
4.1×10^{-2}	4.73×10^{-5}	1.34×10^{-1}	1

Transmissivity (*T*)		
Square meters per day ($m^2\ d^{-1}$)	Square feet per day ($ft^2\ d^{-1}$)	Gallons per day per foot ($gal.\ d^{-1}\ ft^{-1}$)
1	10.76	80.5
0.0929	1	7.48
0.0124	0.134	1

Recharge rates			
Unit depth per year	Volume		
	($m^3\ d^{-1}\ km^{-2}$)	($ft^3\ d^{-1}\ mi^{-2}$)	($gal.\ d^{-1}\ mi^{-2}$)
(In millimeters)	2.7	251	1,874
(In inches)	70	6,365	47,748

Flow rates				
($m^3\ s^{-1}$)	($m^3\ min^{-1}$)	($ft^3\ s^{-1}$)	($ft^3\ min^{-1}$)	($gal.\ min^{-1}$)
1	60	35.3	2,120	15,800
0.0167	1	0.588	35.3	264
0.0283	1.70	1	60	449
0.000472	0.0283	0.0167	1	7.48
0.000063	0.00379	0.0023	0.134	1

UNITS AND CONVERSIONS

Metric to inch-pound units

LENGTH
1 millimeter (mm) = 0.001 m = 0.03937 in.
1 centimeter (cm) = 0.01 m = 0.3937 in. = 0.0328 ft
1 meter (m) = 39.37 in. 3.28 ft = 1.09 yd
1 kilometer (km) = 1,000 m = 0.62 mi

AREA
1 cm^2 = 0.155 $in.^2$
1 m^2 = 10.758 ft^2 = 1.196 yd^2
1 km^2 = 247 acres = 0.368 mi^2

VOLUME
1 cm^3 = 0.061 $in.^3$
1 m^3 = 1,000 l = 264 U.S. gal. = 35.314 ft^3
1 liter (l) = 1,000 cm^3 = 0.264 U.S. gal.

MASS
1 microgram (μg) = 0.000001 g
1 milligram (mg) = 0.001 g
1 gram (g) = 0.03527 oz = 0.002205 lb
1 kilogram (kg) = 1,000 g = 2.205 lb

Inch-pound to metric units

LENGTH
1 inch (in.) = 25.4 mm = 2.54 cm = 0.0254 m
1 foot (ft) = 12 in. = 30.48 cm = 0.3048 m
1 yard (yd) = 3 ft = 0.9144 m = 0.0009144 km
1 mile (mi) = 5,280 ft = 1,609 m = 1.609 km

AREA
1 $in.^2$ = 6.4516 cm^2
1 ft^2 = 929 cm^2 = 0.0929 m^2
1 mi^2 = 2.59 km^2

VOLUME
1 $in.^3$ = 0.00058 ft^3 = 16.39 cm^3
1 ft^3 = 1728 $in.^3$= 0.02832 m^3
1 gallon (gal.) = 231 $in.^3$ = 0.13368 ft^3 = 0.00379 m^3

MASS
1 ounce (oz) = 0.0625 lb = 28.35 g
1 pound (lb) = 16 oz = 0.4536 kg

ACRONYMS

Acronym	Definition
ABM	Albuquerque basin model
ABQ	Albuquerque
ACS	Arroyo Confluence South
ADS	Activity Data Sheet
AEC	Atomic Energy Commission
AEP	air entry permeameter
AML	ARC macro language
ARG	ancestral Rio Grande
ASTM	American Society for Testing and Materials
AVN	Area V North
AWC	Available Water Capacity
BTEX	benzene, toluene, ethylene and xylene
CA	Corrective Action
CDF	cumulative distribution function
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CHBP	constant-head borehole permeameter
CM	conceptual model
CMI	Corrective Measures Implementation
CMS	Corrective Measures Study
COC	constituents of concern
CoV	coefficient of variation
CSAMT	Controlled Source Audio Magnetotelluric
CTF	Coyote Test Field
CWL	Chemical Waste Landfill
CYA	Coyote Arroyo
D&D	decontamination and demolition or decommissioning
DDE	Dynamic Data Exchange
DNAPL	dense non-aqueous phase liquid
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE/AL	DOE Albuquerque Operations Office
DQO	data quality objective
DTW	depth to water
DU	depleted uranium
EG&G	Edgerton, Germeshausen and Grier, Inc.
EO	Environmental Operations
EOD	Explosive Ordnance Disposal
EP	Environmental Program

ACRONYMS (Continued)

Acronym	Definition
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ER	Environmental Restoration
ER/WM	Environmental Restoration and Waste Management
ERDMS	Environmental Restoration Database Management System
ERGIS	Environmental Restoration Geographic Information System
ESI	Engineering Science, Incorporated
FEM	finite element method
FHWA	Federal Highway Administration
FOP	Field Operating Procedure
FTE	full-time equivalent
FY	fiscal year
GCD	Greater Confinement Disposal
GCDP	Gas Cylinder Disposal Pit
GIS	Geographic Information System
GOCO	government-owned, contractor-operated
GWPMPP	Groundwater Protection Management Program Plan
GWPP	Groundwater Protection Program
H&S	Health and Safety
HE	high explosive
HERMES	High Energy Radiation Megavolt Source
HERTF	High Energy Research Test Facility
HR	Hydrogeologic Region
HSWA	Hazardous and Solid Waste Amendments
ID	inside diameter
IP	Instantaneous Profile
IQD	Interquartile Distance
IRP	Installation Restoration Program
ITRI	Inhalation Toxicology Research Institute
KAFB	Kirtland Air Force Base
LBERI	Lovelace Biomedical and Environmental Research Institute, Inc.
LHS	Latin Hypercube Sampling
LCM	lost circulation material
LMF	Large Melt Facility
LWDS	Liquid Waste Disposal System
MAE	mean absolute error
MBW	Manzano Base West

ACRONYMS (Continued)

Acronym	Definition
ME	mean error
MCL	maximum contaminant level
M.P.	measurement point
MW	monitoring well
MWL	Mixed Waste Landfill
NAT	neutron access tube
NEPA	National Environmental Policy Act
NFA	No Further Action
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
NMED	New Mexico Environment Department
NMSHTD	New Mexico State Highway and Transportation Department
NOAA	National Oceanographic and Atmospheric Administration
NPN	nitrate plus nitrite
NTU	nephelometric turbidity units
OD	outside diameter
OSHA	Occupational Safety and Health Administration
OU	Operable Unit
PARCC	Precision, Accuracy, Representativeness, Completeness and Comparability
PCB	polychlorinated biphenyl
PGS	Parade Ground South
POTW	Publicly Owned Treatment Works
PRC	PRC Environmental Management, Inc.
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RI/FS	Remedial Investigation, Feasibility Study
RMS	root-mean-square error
SAIC	Science Applications International Corporation
SARA	Superfund Amendment and Re-authorization Act
SFG	Santa Fe Group
SFR	South Fence Road
SNL/NM	Sandia National Laboratories, New Mexico
SSE	sum of squared errors
STS	Solar Tower South
STW	Solar Tower West
SV	spatial variability
SVOC	semivolatile organic compounds

ACRONYMS (Concluded)

Acronym	Definition
SVS	soil vapor survey
SWHC	Site-Wide Hydrogeologic Characterization
SWHCP	Site-Wide Hydrogeologic Characterization Project
SWMU	Solid Waste Management Unit
SZ	saturated zone
TA	Technical Area
TAGC	Tijeras Arroyo Golf Course
TAIE	Tijeras Arroyo Infiltration Experiment
TAL	target analyte list
TCE	trichloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
TD	total depth
TDR	Time Domain Reflectometry
TIE	Technology Information Exchange
TJA	Tijeras Arroyo
TMR	telescopic mesh refinement
TPH	total petroleum hydrocarbons
TRE	Thunder Range East
TRN	Target Road North
TRS	Target Road South
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
UST	underground storage tank
UTL	upper tolerance limit
UXO	unexploded ordnance
VCM	Voluntary Corrective Measure
VOC	volatile organic compound
VZ	vadose zone
WQCC	Water Quality Control Commission
WY	water year
WYO	Wyoming and Ordnance Road
XRD	x-ray diffraction

ABBREVIATIONS

Abbreviation	Definition
ac	acre(s)
bgs	below ground surface
Bldg.	building
BMP	below measuring point
Br^-	bromide
$CaCO_3$	calcium carbonate
Cl^-	chloride
cm	centimeter(s)
famsl	feet above mean sea level
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
g	gram(s)
gal.	gallon(s)
gpd	gallons per day
gpm	gallons per minute
gwtt	groundwater travel time
hp	horsepower
hr	hour(s)
in.	inch(es)
km	kilometer(s)
Ma	million years ago
mi	mile(s)
ml	milliliter(s)
min	minute(s)
mm	millimeter(s)
mmho	millimho(s)
mo	month(s)
msl	mean sea level; generally implies feet above msl
my	million years
Na	sodium
ppb	parts per billion
ppm	parts per million
psig	pounds per square inch gage
yd^2	square yards
yd^3	cubic yards
yr	year(s)

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1.0 INTRODUCTION

This report was prepared by the Site-Wide Hydrogeologic Characterization Project of the Environmental Restoration Project at Sandia National Laboratories, New Mexico, for calendar year 1995. This report also includes revisions suggested by the New Mexico Environment Department's Department of Energy Oversight Bureau and draft Environmental Protection Agency comments issued in 1996. This work was supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

This report satisfies the requirements of Section C.2 in Module IV, Special Conditions Pursuant to the 1984 Hazardous and Solid Waste Amendments (HSWA) to the Resource Conservation and Recovery Act (RCRA) for SNL/NM, I.D. NM5890110518, of the RCRA Part B Hazardous Waste Facility Permit issued to the DOE and SNL/NM as co-permittees (EPA 1993). Preparation of this report is required by Section IV. C. of the Permit, which directs the permittee to submit a report that describes the current knowledge of the installation-wide hydrogeological environment. Section 1.1 addresses these regulatory requirements and how they are fulfilled. Section 1.2 explains the technical approach of the SWHC Project. The ER Project is discussed in Section 1.3. (For a thorough overview of SNL/NM or the ER Project, the reader is directed to the Program Implementation Plan for Albuquerque Potential Release Sites [SNL/NM 1994a].)

1.1 REGULATORY REQUIREMENTS

The HSWA is administered by the New Mexico Environment Department (NMED) and provides the regulatory framework for corrective actions (i.e., most ER Project activities) at SNL/NM. A portion of the permit, the HSWA Module (Module IV), defines the principal requirements with which SNL/NM must comply in implementing the ER Project at SNL/NM. The requirements for this report and its supporting studies are found in Section C.2, Installation-Wide Hydrogeologic Environment, of the HSWA Module (EPA 1993). The study of the installation-wide hydrogeologic environment also receives mention in Section C.6, Prioritization of Operable Units. It is the purpose of the SWHC Project to gather pertinent information and conduct studies to meet these requirements for the ER Project. Table 1.1-1 shows the HSWA Module special condition requirements of Section C and where they are addressed in this report. For a more thorough discussion of the regulatory framework of the ER Project, see the Program Implementation Plan for Albuquerque Potential Release Sites (SNL/NM 1994a).

The HSWA Permit does not mandate the inclusion of all contaminant distribution information in the site-wide annual reports. However, hydrogeologic data gathered by the ER Project at individual sites has been included in our assessment of the site-wide hydrogeologic framework.

1.2 TECHNICAL APPROACH

At first, the SWHC Project set out to define its technical approach in a purely quantitative manner. This technical approach was called the "quantitative approach" in the calendar year 1992 and 1993 annual reports (SNL/NM 1993a, 1994b). As explained in the Calendar Year 1994 Report (SNL/NM 1995a), the quantitative approach was abandoned because peer reviewers, project team members, and the U.S. Environmental Protection Agency (EPA) felt the quantitative approach could lead to an

Table 1.1-1. Submission Requirements of HSWA Module That Are Addressed in This Report

HSWA Section C.2 Requirement (EPA 1993)	Location in This Report
The permittee shall submit to the administrative authority a report describing the current knowledge of the installation-wide hydrogeological environment.	This report provides the information.
A summary description of the major features and conceptual interrelationships of the hydrogeological environment.	Section 3.0 describes major features and Section 4.0 describes the conceptual interrelationships of the hydrogeologic environment.
All known reports or work on the geohydrology of the facility shall be included.	All known reports were integrated into the current knowledge presented in this deliverable and the technical reports in the appendices. A completed reference list is included at the end of each section and appendix.
The regional and installation-wide geologic setting and hydrologic characteristics and their associated uncertainties affecting the occurrence, movement, and interaction of surface and subsurface water with a view toward a quantitative understanding of potential pathways for transport of contaminants.	The geologic setting and hydrologic characteristics are described in Section 3.0. The associated uncertainties are found in Section 4.0. Data and interpretations included in the appendix reports directly improve the quantitative understanding of the conceptual model (CM) in Section 4.0. The CM will be the basis for understanding potential pathways.
An annual update shall be prepared that will incorporate the major findings of installation-wide significance from studies conducted under the RCRA Facility Investigations (RFIs) performed.	Section 2.0 lists the various projects with which the SWHC Project regularly works to compile information for its investigations.
This report shall contain detailed maps depicting important hydrogeologic information.	This report contains numerous maps and plates depicting important hydrogeologic information.
HSWA Section C.6 Requirement	**Location in This Report**
Installation-Wide Hydrogeologic Environment Study will provide information to support the DOE ER Priority System.	This report provides the information. The SWHC Project also provides consultation to support the DOE ER Priority System.

oversight or omission in the field characterization. Also, the Program Implementation Plan for Albuquerque Potential Release Sites (SNL/NM 1994a) including the technical approach for the ER Project, was approved in 1994. The final approved technical approach of the SWHC Project includes the following steps:

1. Information gathering and evaluation
2. Conceptual model development
3. Development of data criteria for decision making
4. Establishment of Data Quality Objectives (DQOs)
5. Development of sampling and analysis plans

(See Section 4.0 of the Program Implementation Plan for Albuquerque Potential Release Sites [SNL/NM 1994a].)

These general steps are applied to the SWHC Project in the following manner. Step 3 is the submission of this report, which presents Steps 1 and 2. Steps 4 and 5 are the plans for the numerous studies conducted by the SWHC Project. The results of these studies fill information gaps left by Steps 1 and 2. These iterative steps, repeated annually since 1992, have been the cornerstone for uncovering information gaps and identifying future studies. Progressing from Step 3 to Steps 4 and 5 includes considering ER Project priorities, working with regulator comments, seeking synergies with other ER activities (for example, could a well drilled for the SWHC Project also serve as a monitoring well for an ER Project site?), and seeking synergies with programs outside the ER Project (such as SNL/NM's Groundwater Protection Project, Environmental Restoration Projects at Kirtland Air Force Base [KAFB] and the Inhalation Toxicology Research Institute [ITRI] facility, the City of Albuquerque Public Works Department, etc.).

1.3 THE SITE-WIDE HYDROGEOLOGIC CHARACTERIZATION PROJECT AND THE ENVIRONMENTAL RESTORATION PROJECT AT SANDIA NATIONAL LABORATORIES/NEW MEXICO

The environment described in this report is located within the boundaries of KAFB and adjacent lands managed by other government agencies (shown on Plates I and II). The area is called the SNL/KAFB area throughout this report. Figure 1.3-1 shows where the area is in New Mexico.

The SNL/KAFB area encompasses 52,223 acres (ac) bounded on the north and northwest by the City of Albuquerque, New Mexico; on the east by Cibola National Forest; on the south by the Isleta Pueblo; and on the west by land owned by the State of New Mexico, KAFB (buffer zones), and the Albuquerque International Airport. There are two restricted-access buffer zones on the southwest corner of the site that separate public access areas and the Isleta Pueblo from KAFB and SNL/NM operations. SNL/NM occupies 2820 ac within KAFB. It consists of five main work areas called technical areas and additional test areas, such as Thunder Range south of Technical Area III (TA-III) and Coyote Canyon Test Field in the canyons on the east side of the Manzano Mountains (also called the Manzano Base).

In addition to general information about the SNL/KAFB area, Plate I shows the location of the 155 sites managed by SNL/NM's ER Project. These 155 sites are called ER Sites or Solid Waste Management Units (SWMUs). The SWMUs are grouped into sets called Operable Units (OUs). The OU groupings are shown on Plate I by color. Each SWMU is identified by its number. Refer to Table 1.3-1 for the name of each SNL/NM SWMU in the SNL/KAFB boundaries and its Site Priority Ranking on December 31, 1995. (The relative ranking of sites is used by ER Project management to help prioritize resource allocations to SWMU activities [SNL/NM 1994a, Annex I, Section 1.2.11].) Plate II also shows the SNL/NM SWMUs, along with the wells in the SNL/KAFB area and the sites managed by KAFB.

To be of most benefit to the ER Project at SNL/NM, the SWHC Project conducted most of its studies while the OUs were in the early stages of the corrective action process. Table 1.3-2 shows at what stage ER sites were in the corrective action process by the end of 1995. The table also lists activities such as Voluntary Corrective Measures (VCMs) and No Further Action (NFA) proposals (SNL/NM 1994d, 1995c, 1995d). A VCM is a voluntary cleanup SNL/NM undertakes before completing the corrective action process. An NFA proposal is a report made to the regulator showing that there is no threat to public or environmental health posed by the subject site and proposing to stop any further study or cleanup of the site (i.e., it explains why the job is finished at that site).

Table 1.3-1. Solid Waste Management Units of Each Operable Unit and Site Priority Ranking (See Plate I for Location)

Site Number	Site	Priority Ranking[a]
Mixed Waste Landfill Operable Unit		
76	Mixed Waste Landfill	42
Septic Tanks and Drainfields Operable Unit		
49	Bldg. 9820 Drains	44
101	Explosive Contaminated Sumps, Drains (Bldg. 9926)	22
116	Bldg. 9990 Septic System	32
137	Bldg. 6540/6542 Septic System	19
138	Bldg. 6630 Septic System	24
139	Bldg. 9964 Septic System	22
140	Bldg. 9965 Septic System	28
141	Bldg. 9967 Septic System	22
142	Bldg. 9970 Septic System	26
143	Bldg. 9972 Septic System	26
144	Bldg. 9980 Septic System	29
145	Bldg. 9981/9982 Septic Systems	29
146	Bldg. 9920 Drain System	22
147	Bldg. 9925 Septic Systems	31
148	Bldg. 9927 Septic System	28
149	Bldg. 9930 Septic System	33
150	Bldg. 9939/9939A Septic Systems	28
151	Bldg. 9940 Septic System	28
152	Bldg. 9950 Septic System	17
153	Bldg. 9956 Septic Systems	15
154	Bldg. 9960 Septic Systems	33
160	Bldg. 9832 Septic System	31
161	Bldg. 6636 Septic System	28
Technical Area I Operable Unit		
25	Burial Site (South of TA-I)	24
30	PCB Spill (Reclamation Yard)	43
32	Steam Plant Oil Spill	31
33	Motor Pool Oil Spill	42
41	Bldg. 838 Mercury Spill	25
42	Acid Spill Water Treatment Facility	47
73	Hazardous Waste Repackaging/Storage (Bldg. 895)	31
96	Storm Drain System (Active)	47
98	Bldg. 863, TCA Photochemical Releases: Silver Catch Boxes	42
104	PCB Spill, Computer Facility	8
186	TCE Dumping South of Bldg. 859	46
187	Septic Tank Piping for POTW	54
190	Tank Farm for Steam Plant	51
192	TA-I Waste Oil Tank	42
226	Acid Waste Line	56

[a]High = 40 and higher.
Medium = 25-39.
Low = 24 and lower.

Table 1.3-1. Solid Waste Management Units of Each Operable Unit and Site Priority Ranking (See Plate I for Location) (Continued)

Site Number	Site	Priority Ranking[a]
Technical Area II Operable Unit		
1	Radioactive Waste Landfill	64
2	Classified Waste Landfill	65
3	Chemical Disposal Pit	64
43	Radioactive Material Storage Yard	67
44	Decontamination Site and Uranium Calibration Pits	57
48	Bldg. 904 Septic System	62
113	Area II Firing Sites	58
114	Explosive Burn Pit	54
135	Bldg. 906 Septic System	62
136	Bldg. 907 Septic System	62
159	Bldg. 935 Septic System	61
165	Bldg. 901 Septic System	53
166	Bldg. 919 Septic System	61
167	Bldg. 940 Septic System	61
Technical Areas III and V Operable Unit		
18	Concrete Pad	26
26	Burial Site (West of TA-III)	21
31	Electrical Transformer Oil Spill	28
34	Centrifuge Oil Spill	24
35	Vibration Facility Oil Spill	22
36	Oil Spill - HERMES	31
37	PROTO Oil Spill	25
51	Bldg. 6924 Pad, Tank, Pit	33
78	Gas Cylinder Disposal Pit	46
83	Long Sled Track	22
84	Gun Facilities	28
100	Bldg. 6620 HE Sump/Drain	17
102	Radioactive Disposal (East of TA-III)	21
105	Mercury (Bldg. 6536)	3
107	Explosive Test Area (Southeast TA-III)	22
111	Bldg. 6715 Sump/Drains	14
188	Bldg. 6597 Above-Ground Containment Spill Tank	8
196	Bldg. 6597 Cistern	24
240	Short Sled Track	22
241	Storage Yard	26
Liquid Waste Disposal System (LWDS) Operable Unit		
4	LWDS Surface Impoundments	21
5	LWDS Drainfield (TA-V)	15
52	LWDS Holding Tanks (TA-V)	19

[a]High = 40 and higher.
Medium = 25-39.
Low = 24 and lower.

Table 1.3-1. Solid Waste Management Units of Each Operable Unit and Site Priority Ranking (See Plate I for Location) (Continued)

Site Number	Site	Priority Ranking[a]
Tijeras Arroyo Operable Unit		
7	Gas Cylinder Disposal (Arroyo del Coyote)	46
16	Open Dumps (Arroyo del Coyote)	56
23	Disposal Trenches (Near Tijeras Arroyo)	49
40	Oil Spill (6000 Igloo Area)	17
45	Liquid Discharge (Behind TA-IV)	69
46	Old Acid Waste Line Outfall (Tijeras Arroyo)	56
50	Old Centrifuge Site (TA-II)	57
77	Oil Surface Impoundment (TA-IV)	17
227	Bunker 904 Outfall (from TA-II)	74
228	Centrifuge Dump Site	57
229	Storm Drain System Outfall	68
230	Storm Drain System Outfall	68
231	Storm Drain System Outfall	68
232	Storm Drain System Outfall	68
233	Storm Drain System Outfall	68
234	Storm Drain System Outfall	68
235	Storm Drain System Outfall	68
Foothills Test Area Operable Unit		
8	Open Dump (Coyote Canyon Blast Area)	65
15	Trash Pits (Frustration Site)	42
19	TRUPAK Boneyard Storage Area (NW of Old Aerial Cable)	54
28	Mine Shafts	53
58	Coyote Canyon Blast Area	65
66	Boxcar Site	51
67	Frustration Site	54
82	Old Aerial Cable Site Scrap	61
87	Bldg. 9990 (Firing Site)	51
Canyons Test Area Operable Unit		
10	Burial Mounds (Bunker Area North of Pendulum Site)	54
12	Burial Site/Open Dump (Lurance Canyon)	60
13	Oil Surface Impoundment (Lurance Canyon Burn Site)	57
59	Pendulum Site	25
60	Bunker Area (North of Pendulum Site)	54
63	Balloon Test Area	39
64	Gun Site (Madera Canyon)	21
65	Lurance Canyon Explosive Test Site	60
72	Operation Beaver Site	21
81	New Aerial Cable Site/Burial Site/Dump/Test Area	68
27	Bldg. 9820 - Animal Disposal Pit (Coyote Springs)	54
92	Pressure Vessel Test Site (Coyote Canyon Blast Area)	46
93	Madera Canyon Rocket Launcher Pads	29
94	Lurance Canyon Burn Site	60
225	AEC Storage Facility/KAFB	51

[a]High = 40 and higher.
Medium = 25-39.
Low = 24 and lower.

Table 1.3-1. Solid Waste Management Units of Each Operable Unit and Site Priority Ranking (See Plate I for Location) (Concluded)

Site Number	Site	Priority Ranking[a]
	Central Coyote Test Area Operable Unit	
9	Burial Site/Open Dump (Schoolhouse Mesa)	47
11	Radioactive/Explosive Burial Mounds	32
20	Uranium Burn Site (Schoolhouse Mesa)	19
21	Metal Scrap (Coyote Springs)	43
22	Storage/Burn (West of DEER)	36
47	Doomed Bunker Outfall (South KAFB Boundary)	43
57	Workman Site	32
61	Schoolhouse Mesa Test Site	26
62	Greystone Manor Site (Coyote Springs)	28
68	Old Burn Site	47
69	Firing Pits (Near USGS)	24
70	Explosives Test Pit (Water Towers)	28
71	Moonlight Shot Area	47
88	Firing Site (Southwest of Coyote Springs)	28
	Southwest Test Area Operable Unit	
6	Gas Cylinder Disposal Pit (Bldg. 9966)	42
14	Burial Site (Bldg. 9920)	39
17	Scrap Yards/Open Dump (Thunder Range)	32
38	Oil Spills (Bldg. 9920)	33
39	Oil Spill - Solar Facility	21
53	Bldg. 9923	4
54	Pickax Site (Thunder Range)	38
55	Red Towers Site (Thunder Range)	40
56	Old Thunderwells (Thunder Range)	33
85	Firing Site (Bldg. 9920)	44
86	Firing Site (Bldg. 9927)	46
89	Shock Tube Site (Thunder Range)	40
90	Beryllium Firing Site (Thunder Range)	40
91	Lead Firing Site (Thunder Range)	38
103	Scrap Yard (Bldg. 9939)	49
108	Firing Site (Bldg. 9940)	50
109	Firing Site (Bldg. 9956)	51
112	Explosive Contaminated Sump (Bldg. 9956)	29
115	Firing Site (Bldg. 9930)	43
117	Trenches (Bldg. 9939)	40
191	Equus Red	38
193	Sabotage Test Area	36
194	General Purpose Heat Source Test Area	28
	Chemical Waste Landfill Operable Unit	
74	Chemical Waste Landfill	40

[a]High = 40 and higher.
Medium = 25-39.
Low = 24 and lower.

Table 1.3-2. ER Project Progress

Operable Unit	Progress as of December 31, 1995
Mixed Waste Landfill	RFI Work Plan approved (SNL/NM 1993b) RFI Report in preparation (due September 1996)
Septic Tanks and Drainfields	RFI Work Plan approved (SNL/NM 1993c) NFAs submitted for SWMUs 142, 143, 146, 148 NFA approved for SWMU 139
Technical Area I	RFI Work Plan submitted to EPA (SNL/NM 1995b) NFAs accepted by EPA for SWMUs 25, 32, 41, 73, 104 (SWMU 187/226)
Technical Area II	NFAs submitted for SWMUs 3, 43, 44, 113, 135, 165, 48, 136, 159, 166, 167 VCMs performed at SWMUs 44, 114 VCM plan submitted at SWMUs 1, 2
Technical Areas III and V	RFI Work Plan approved (SNL/NM 1993d) RFI Report in preparation (due March 1995) NFAs accepted by EPA for SWMUs 105, 188 NFA submitted for SWMU 195 VCM performed at SWMU 78
Liquid Waste Disposal System	RFI Work Plan approved (SNL/NM 1993e) RFI Report submitted (recommends NFA at SWMUs 4, 5, 52)
Tijeras Arroyo	VCM performed at Site 232 NFAs submitted for SWMUs 7, 23, 40, 46, 50, 77, 227, 229, 230, 231, 233, 234, 235
Foothills Test Area	RFI Work Plan submitted to EPA NFAs submitted for SWMUs 15, 27, 28, 67
Canyons Test Area	RFI Work Plan submitted to EPA NFAs submitted for SWMUs 72, 93a, 93b, 93c, 59, 63a, 63b, 64, 92, 225
Central Coyote Test Area	RFI Work Plan submitted to EPA (SNL/NM 1994c) NFAs accepted by EPA for SWMUs 20, 47, 62, 69, 88a NFAs submitted for SWMUs 21, 47, 62, 69, 71, 88a, 22, 61b General Housekeeping performed at SWMUs 22, 47, 57b General Housekeeping pending at SWMU 21
Southwest Test Area	RFI Work Plan in preparation NFAs submitted for SWMUs 39, 53, 194 VCMs performed at SWMUs 6, 6a
Surface Radiation VCM	Completed at Technical Area III/V (SWMUs 18, 240, 83, 84), Tijeras Arroyo (SWMUs 16, 228), Foothills Test Area (SWMUs 27, 8, 58, 87), Southwest Test Area (SWMUs 108, 14/85, 191, 17B, 193, 103, 55), Canyons Test Area (SWMUs 10/60, 94), Central Coyote Test Area (SWMUs 88, 57, 61A, 71/68) Expanded work in 1996 (pending funding): 71/68, 61A, 10/60

1.4 REFERENCES

EPA, 1993. U.S. Environmental Protection Agency. Hazardous Waste Permit to SNL and DOE, Module IV, Special Conditions Pursuant to the 1984 HSWA to the RCRA for SNL/NM, EPA I.D. NM5890110518.

SNL/NM, 1993a. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1992 Annual Report. SAND93-0681, Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1993b. Sandia National Laboratories/New Mexico. Mixed Waste Landfill Phase 2 RCRA Facility Investigation Work Plan, March 31, 1993. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1993c. Sandia National Laboratories/New Mexico. Septic Tanks and Drainfields (ADS 1295) RCRA Facility Investigation Work Plan, March 1993. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1993d. Sandia National Laboratories/New Mexico. Technical Areas 3 and 5 RCRA Facility Investigation Work Plan, March 1993, Addendum November 1993. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1993e. Sandia National Laboratories/New Mexico. Liquid Waste Disposal System RCRA Facility Investigation Work Plan, March 1993. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994a. Sandia National Laboratories/New Mexico. Program Implementation Plan for Albuquerque Potential Release Sites, prepared for the U.S. Department of Energy/Albuquerque Operations Office. Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994b. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1993 Annual Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994c. Sandia National Laboratories/New Mexico. RCRA Facility Investigation Work Plan for Operable Unit 1334 Central Coyote Test Area, October 1994. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994d. Sandia National Laboratories/New Mexico. August 1994, Proposals for Administrative No Further Action, FY94, Environmental Restoration Project, Sandia National Laboratories/New Mexico, for the U.S. Department of Energy/Albuquerque Operations Office, Albuquerque, NM.

SNL/NM, 1995a. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1994 Annual Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995b. Sandia National Laboratories/New Mexico. Technical Area I (ADS 1302) RCRA Facility Investigation Work Plan, February 1995. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995c. Sandia National Laboratories/New Mexico. June 1995, Proposals for No Further Action, FY 1995. Environmental Restoration Project, Sandia National Laboratories/New Mexico, for the U.S. Department of Energy/Albuquerque Operations Office, Albuquerque, NM.

SNL/NM, 1995d. Sandia National Laboratories/New Mexico. August 1995, Proposals for No Further Action, FY 1995. Environmental Restoration Project, Sandia National Laboratories/New Mexico, for the U.S. Department of Energy/Albuquerque Operations Office, Albuquerque, NM.

2.0 ENVIRONMENTAL CHARACTERIZATION ACTIVITIES PERFORMED ON THE KIRTLAND AIR FORCE BASE FACILITY

The SWHC Project integrates pertinent information from all known reports or studies related to the hydrogeology of the facility into the site-wide hydrogeologic conceptual model. The usual focus of such studies is the nature and extent of contamination of a smaller area within the facility, such as an SWMU, and not the hydrogeology of the facility. Nevertheless, those studies often generate small sets of hydrogeologic information that, when assembled, contribute to a useful installation-wide description or big picture.

Section 2.1 lists the activities performed by the SWHC Project. Section 2.2 describes the type of hydrogeologic data that may be generated by activities performed at SWMUs. Sections 2.3 through 2.7 indicate entities outside the SNL/NM ER Project that have performed environmental characterization activities which contributed in varying degrees to current knowledge of the installation-wide hydrogeology. The larger-scale studies performed by the SWHC Project and the smaller data sets from other projects are compiled to assemble the descriptions and conceptual models described in Sections 3.0 and 4.0.

2.1 SITE-WIDE HYDROGEOLOGIC CHARACTERIZATION PROJECT

The SWHC Project has performed many activities to improve the current knowledge of the installation-wide hydrogeologic environment. This report presents a summary description of the major features and conceptual interrelationships of the facility's hydrogeologic environment in Sections 3.0 and 4.0, respectively. Furthermore, reports in the appendices and attachments provide details pertaining to recent studies performed by the SWHC Project in order to improve these descriptions. Use Table 2.1-1 and the Contents as a guide to the appendix and attachment reports.

2.2 SANDIA NATIONAL LABORATORIES/NEW MEXICO OPERABLE UNIT PROJECTS

As described in Section 1.0 and in the Program Implementation Plan for Albuquerque Potential Release Sites (SNL/NM 1994), the ER Project manages the corrective action process at SNL/NM. Although the activities conducted under this process are intended to address the nature and extent of contamination concerns at specific SWMUs, the geologic and hydrologic information gathered as part of the corrective action process can be used in the descriptions in this report. (Table 1.3-2 shows progress made at the various SNL/NM OUs.) These types of information will be used and referenced throughout this report and its appendices.

The different types of information that may be collected as part of an OU study and which potentially contribute to site-wide hydrogeologic descriptions or conceptual models are described below. Examples within this report using each type of information are also provided.

1. Soil sampling: In addition to chemical analysis, some soils receive hydrologic analysis that may contribute to geologic and hydrologic descriptions. See Section 3.2.4.

Table 2.1-1. Project Activities That Contributed to the Hydrogeologic Conceptual Model

Tasks	Type of Activity	Type of Data Collected			
		Lithologic	Geophysical	Hydrologic	Geochemical
Site-Wide Geology (Attachment 1)	Geologic data assessment Surface and subsurface mapping Geologic conceptual model	x	x	x	
Arroyo Investigations (Appendix A)	Arroyo infiltration studies Streamflow gaging Surface water quality	x		x	x
Vadose Zone Studies (Appendix B and Attachment 3)	Infiltration studies		x	x	x
Computer Modeling (Attachment 4)	Groundwater flow modeling	x		x	
Saturated Zone Studies (Appendices C and D and Attachment 2)	Aquifer testing Well drilling Geochemistry studies	x	x	x	x

2. Groundwater sampling: In addition to chemical analysis, some samples receive geochemical analysis. See Section 3.2.4.3.5.

3. Slug tests and aquifer pumping tests: These tests are performed to develop an understanding of the basic aquifer parameters controlling the flow of water in the aquifer being tested. The results may be used in regional flow models and to assess contaminant transport. See Appendix D and Plate III.

4. Groundwater elevation measurements: These measurements can be used to describe and map the water table. See Plate IV and Figures 3.2.4-3 and 3.2.4-4.

5. Monitoring well installation: The wells provide measuring points for groundwater chemistry and elevation (see above). The core and cuttings collected during installation contribute to geologic descriptions and may be sent to a hydrology lab for hydrologic characterization. Geophysical measurements made in the well also contribute to geologic descriptions. Plate II shows all the wells on the facility. See Section 3.1 and Attachment 1 for geologic descriptions that used well data and Appendix C for a summary of the SWHC Project 1995 well installations.

2.3 SANDIA NATIONAL LABORATORIES/NEW MEXICO GEOGRAPHIC INFORMATION SYSTEM

The SWHC Project has been one of the largest users of a Geographic Information System (GIS) available to the ER Project at SNL/NM. This GIS maintains an ARC/INFO GIS database that contains more than 1000 data layers that represent the environmental and physical characteristics of entities within the SNL/KAFB area. In addition to most of the custom maps in this report, the GIS also provides the following products and services to the SWHC Project: databases of analytical sample results, physical well data, groundwater level data, etc.; a global positioning system; and groundwater modeling support. See Sections 2.7, 3.2.4, and 3.2.5 and Attachment 4 for more on groundwater modeling.

The GIS maps and data in this report and other reports remain with GIS and are made available to all SNL/NM environmental projects. The GIS provides a common point where information is consolidated from environmental projects at SNL/NM and, to a lesser extent, KAFB (Plate II, for example). The GIS is an example of how OU and site-wide information is shared across the ER Project.

2.4 SANDIA NATIONAL LABORATORIES/NEW MEXICO GROUNDWATER PROTECTION PROGRAM

DOE Order 5400.1, General Environmental Protection Program (DOE 1988), establishes requirements for the general protection of the environment through pollution prevention, monitoring, and surveillance activities that assess the impacts of DOE operations on the environment and demonstrate compliance with applicable federal, state, and local environmental laws and regulations. A major focus of the program is the protection of groundwater resources. This is attained through the prevention of groundwater contamination by emphasizing waste minimization; mandating appropriate waste disposal, spill prevention, or containment; and requiring prompt cleanup of spills and remediation of contamination if necessary.

One aspect of groundwater protection is to monitor for potential movement of contaminated groundwater through the installation through operation of monitor wells and boreholes. The program has implemented a registry of all wells and boreholes at SNL/NM. One function of the registry is the permitting of wells and boreholes and the institution of a regular inspection and maintenance schedule. An additional function is the establishment of a database for all relevant well-construction information. An equally important function of the well registry is to document the plugging and abandonment of wells. An adjunct of the registry is a records system for documenting and tracking relevant information on well design, installation, and operation.

To evaluate the effectiveness of the groundwater protection measures and demonstrate compliance with regulations, the Groundwater Protection Program conducts groundwater surveillance. In March of 1995, samples were collected from 16 wells and 4 springs throughout the SNL/KAFB area. Sample analyses provide data on physical and chemical water-quality indicators. Specific analytes include 20 metals, 5 anions, 6 cations, 12 radioisotopes, pesticides, and volatile organic compounds (VOCs). Monthly water levels are measured in 36 wells. Water-level measurements are used to establish historical trends through well hydrographs and the construction of potentiometric surface maps that may be used to determine groundwater gradients and infer groundwater flow directions. Groundwater data collected by the SNL/NM Groundwater Surveillance task as well as groundwater monitoring activities by SNL/NM ER activities are reported in the Groundwater Protection Program annual report (SNL/NM 1995).

2.5 KIRTLAND AIR FORCE BASE INSTALLATION RESTORATION PROGRAM

The Installation Restoration Program (IRP) at KAFB is similar to SNL/NM's ER Project and therefore generates the same types of information as the SNL/NM OUs (see Section 2.2 above). As shown on Plate II, ER and IRP geographically share much of the same area of the facility. Therefore, ER and IRP work together to share reports, information, and sometimes activities.

The U.S. Department of Defense (DoD) has implemented the IRP to comply with the provisions of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 and the Superfund Amendments and Reauthorization Act (SARA) of 1986. The purpose of the IRP is to identify, quantify, and correct conditions that could result in soil and groundwater contamination and possible migration of contaminants beyond DoD installation boundaries. The IRP is typically executed in four phases: Phase I - Problem Identification/Records Search, Phase II - Problem Confirmation/ Quantification, Phase III - Technology Base Development, and Phase IV - Operations/Remedial Actions.

Phase I was conducted in 1981. This phase concluded with a report that described the KAFB facilities, base history and environmental setting, and the Engineering Science, Inc. (ESI) findings and recommendations (ESI 1981). Phase II activities have taken place in several stages. Phase II - Stage 1, conducted from 1983 through 1985, included preliminary field investigations at the six highest priority sites identified during Phase I. These preliminary investigations consisted of aerial image analyses, surface seismic refraction surveys at selected locations, auger borings, installation of slant lysimeters and groundwater monitoring wells, and chemical sampling of selected soil and water samples (SAIC 1985). Since 1985, Phase II investigation stages were added and performed to continue to characterize the sites, identify the nature and extent of potential contamination, and develop recommendations for a follow-on RCRA corrective action program (USGS 1993a, 1993b). By the end of 1995, Phase II was still in progress.

Also in 1995 a groundwater monitoring program was established. The IRP joined SNL/NM's Background Concentration Study for Constituents of Concern (COCs). (No reports were completed on these studies in 1995.)

2.6 INHALATION TOXICOLOGY RESEARCH INSTITUTE ENVIRONMENTAL RESTORATION

ITRI is a DOE-owned, contractor-operated research laboratory. The Lovelace Biomedical and Environmental Research Institute Inc. (LBERI) manages and operates ITRI under a cost-reimbursable, no-fee contract with the DOE. The institute is located on KAFB along its southern boundary, southeast of the DOE solar facility and about 7 miles (mi) southeast of SNL/NM TA-I (see Plate I). ITRI encompasses 135 ac, of which approximately 40 ac are developed.

Through the 1960s and 1970s, the ITRI research program was concerned with human health effects from inhalation exposure to airborne radioactive fission products, but since the early 1980s, its emphasis has shifted to more generalized research with increased emphasis on the biological response to materials inhaled by the respiratory tract.

Past ITRI facility operations may have caused soil and groundwater contamination. In order to evaluate the nature and extent of this potential contamination and to identify and implement suitable cleanup actions, ITRI has developed an Environmental Restoration and Waste Management (ER/WM) Five-Year Plan (ITRI 1990). In response to this plan, several investigations have been completed that include local geologic and hydrologic information. In addition, cleanup efforts have also been undertaken. Reports on these investigations and cleanup efforts were published by ITRI (1991, 1994a, 1994b) and PRC Environmental Management, Inc. (PRC) (1990, 1992, 1993a, 1993b, 1993c). ITRI has recently completed further investigations in response to questions raised by the NMED. Reports on these investigations are currently being prepared. To supplement these investigations, NMED has initiated an independent investigation directly south of ITRI on Isleta Pueblo (McDonald 1994).

Although ITRI is a small facility relative to SNL/NM or KAFB, Plate II shows that many wells were drilled as a part of ITRI investigations. The information from those wells is integrated into the SWHC hydrogeologic conceptual model.

2.7 U.S. GEOLOGICAL SURVEY/CITY OF ALBUQUERQUE PUBLIC WORKS

In 1995, the USGS conducted a water resources investigation that modeled Albuquerque basin groundwater flow from 1901 to 1994, with projections to 2020 (Kernodle et al. 1995). The project was conducted for and in cooperation with the City of Albuquerque Public Works Department. Its purpose was to estimate groundwater flow in the Albuquerque basin and project changes in supply through 2020. (Figure 3.1.1-1 shows the Albuquerque basin.) The SNL/KAFB area is within the boundaries of this Albuquerque basin model (ABM). The details of the ABM were too gross to affect the details of the current knowledge of the SNL/KAFB installation-wide hydrogeologic environment. However, as described in Section 3.2.5 and Attachment 4, the SWHC Project has extracted the SNL/KAFB portion from this model and has begun to add local detail in order to model groundwater flow at SNL/KAFB. In 1996, the ER Project will begin to add a contaminant transport capability to the model. Moreover, this modeling approach uses MODFLOW, which, as mentioned by EPA, Region VI, is a more conventional and well-established approach (EPA 1995). The modeling approach uses this report and the GIS (see above) as its sources of hydrogeologic and geographic information.

2.8 REFERENCES

DOE, 1988. General Environmental Protection Plan, Order 5400.1, U.S. Department of Energy, Washington, D.C. (1988, change 1, June 21, 1990).

EPA, 1995. Environmental Protection Agency Region VI. Memorandum from David Neleigh, Chief New Mexico - Federal Facilities Section, to Michael Zamorski, Department of Energy Kirtland Area Office Acting Area Manager, General Comment #3, 10/30/95.

ESI, 1981. Engineering Science, Inc. Installation Restoration Program, Phase I, Kirtland AFB, Tyndall AFB, Florida.

ITRI, 1990. Inhalation Toxicology Research Institute. Environmental Restoration and Waste Management Five-Year Plan, Site-Specific Plan, LMF-125. ITRI, Kirtland Air Force Base, Albuquerque, NM.

ITRI, 1991. Inhalation Toxicology Research Institute. Site Environmental Report-1990, LMF-131. ITRI, Kirtland Air Force Base, Albuquerque, NM.

ITRI, 1994a. Inhalation Toxicology Research Institute. Site Environmental Report-1992, ITRI-141. ITRI, Kirtland Air Force Base, Albuquerque, NM.

ITRI, 1994b. Inhalation Toxicology Research Institute. Site Environmental Report-1993, ITRI-143. ITRI, Kirtland Air Force Base, Albuquerque, NM.

Kernodle, J. M., D. P. McAda, and C. R. Thorn, 1995. Simulation of Groundwater Flow in the Albuquerque Basin, Central New Mexico, 1901-1994, with Projections to 2020. Water Resources Investigation Report 94-4251 prepared in cooperation with the City of Albuquerque Public Works Department.

McDonald, W., 1994. Memo to File - Preliminary Report on NMED/DOE Oversight Monitoring Well Installation on the Pueblo of Isleta South of DOE ITRI Facility, New Mexico Environment Department, Albuquerque, NM.

PRC, 1990. PRC Environmental Management, Inc. ITRI Lagoon Hydrogeological Study, prepared for the Inhalation Toxicology Research Institute, Kirtland Air Force Base, Albuquerque, NM.

PRC, 1992. PRC Environmental Management, Inc. Monitoring Well Installation Summary Report, prepared for the Inhalation Toxicology Research Institute, Kirtland Air Force Base, Albuquerque, NM.

PRC, 1993a. PRC Environmental Management, Inc. Diesel Oil Release Assessment Program Hydrogeologic Investigation Report, prepared for the Inhalation Toxicology Research Institute, Kirtland Air Force Base, Albuquerque, NM.

PRC, 1993b. PRC Environmental Management, Inc. Groundwater Protection Management Program Plan, prepared for the Inhalation Toxicology Research Institute, Kirtland Air Force Base, Albuquerque, NM.

PRC, 1993c. PRC Environmental Management, Inc. Alluvial Aquifer Characterization - April 1993, prepared for the Inhalation Toxicology Research Institute, Kirtland Air Force Base, Albuquerque, NM.

SAIC, 1985. Science Applications International Corporation. Installation Restoration Program, Phase II, Confirmation/Quantification - Stage 1, Final Report for Kirtland Air Force Base, Albuquerque, NM.

SNL/NM, 1994. Sandia National Laboratories/New Mexico. Program Implementation Plan for Albuquerque Potential Release Sites, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995. Sandia National Laboratories/New Mexico. Groundwater Protection Program Calendar Year 1994 Annual Report, Sandia National Laboratories/New Mexico, Albuquerque, NM.

USGS, 1993a. U.S. Geological Survey. Installation Restoration Program, Phase II - Stage 2, RI/FS Technical Report for Kirtland Air Force Base, New Mexico, USGS Water Resource Division, Albuquerque, NM.

USGS, 1993b. U.S. Geological Survey. Installation Restoration Program, Phase II - Stage 2A, RI/FS Technical Report for Kirtland Air Force Base, New Mexico, USGS Water Resource Division, Albuquerque, NM.

3.0 SITE-WIDE HYDROGEOLOGIC SETTING

This section provides a summary description of the current state of knowledge of the SNL/KAFB hydrogeologic setting. This summary description integrates all relevant information from existing reports, from ongoing environmental programs in the Albuquerque and KAFB area, and from SNL/NM ER Project investigations. Section 3.1 describes the stratigraphic, structural, and geomorphic elements of the local geologic framework. Section 3.2 describes all elements of the local hydrologic system including meteorology, surface water, vadose zone, and saturated zone. In addition, there are brief summaries of new interpretations of the geology and hydrology of the area with appropriate references to the appendices and attachments. These appendices and attachments contain the detailed technical descriptions and discussions that led to the improved understanding of the settings.

Understanding the hydrogeologic framework is a critical first step in approaching problems regarding contaminant transport and risk-based assessments. Geologic and hydrologic factors outside of individual ER site investigations have a direct bearing on such issues as infiltration rates and direction of groundwater flow. Identification of a defensible hydrogeologic framework for the SNL/KAFB area is necessary to reduce uncertainties pertaining to environmental assessment.

3.1 REGIONAL GEOLOGIC SETTING

This summary overview of the SNL/KAFB regional and areal geologic setting within the central Albuquerque basin integrates all relevant information from existing reports and publications, from ongoing non-SNL/NM environmental programs in the Albuquerque and KAFB areas, and from ongoing SNL/NM ER Project investigations. Attachment 1 of this report, Conceptual Geologic Model of the Sandia National Laboratories and Kirtland Air Force Base (GRAM, Inc. 1995), contains the results and conclusions of the geologic investigation conducted for the SNL/NM SWHC Project and should be referred to for detailed information regarding the discussions contained in this section.

The purpose of describing the geologic setting is to provide an overall framework for a better understanding of geologic factors that affect the SNL/KAFB hydrogeology. Geologic factors known to affect contaminant flow paths from the surface into and through the vadose zone, and ultimately into the saturated zone, include: (1) the degree of soil development on the present surface, (2) the original flow direction and depositional characteristics of buried sediments, (3) the major faults and fractures as potential barriers or seepage surfaces, (4) the diagenesis of sediments from infiltration or groundwater flow causing increased or decreased porosity, and (5) the role and influence of underlying indurated and fractured bedrock. Understanding these and other geologic factors will significantly reduce the uncertainty in risk-based assessments by providing data-supported evaluations and predictions that could otherwise only be attained through extensive and expensive invasive investigations.

Knowledge of the geologic framework is an important element in developing a viable conceptual hydrogeologic model, and subsequently solving problems involving contaminant transport and risk-based assessments. Geologic factors outside individual ER site investigation boundaries have direct bearing on issues such as infiltration rates, dispersion characteristics, and groundwater flow directions. Identification of a defensible geologic framework and subsequent construction of a viable conceptual hydrogeologic model for the SNL/KAFB area is necessary to reduce environmental assessment uncertainties.

Section 3.1.1 describes the tectonic framework of the Albuquerque basin as it relates to the SNL/KAFB area. Section 3.1.2 describes all of the known rock units that exhibit characteristics as relevant flow path media within the surface, vadose, and saturated zones of the SNL/KAFB area. Sections 3.1.3 and 3.1.4 discuss the geomorphologic and soil characteristics in the SNL/KAFB area.

3.1.1 Tectonic Setting

The SNL/KAFB site lies within the northern portion of the Mexican Highland section (Rio Grande subsection) of the Basin and Range physiographic province (Hawley 1986). Elevations within the Albuquerque area range from 4900 feet (ft) (1494 meter [m]) along the Rio Grande to approximately 11,000 ft (3354 m) at the crest of the east-bounding Sandia Mountains. Elevations within the SNL/KAFB area, immediately south of the City of Albuquerque, range from 4920 ft (1500 m) adjacent to the Rio Grande to 7988 ft (2435 m) at Manzano Lookout Tower. SNL/KAFB has a mean elevation of 5350 ft (1630 m).

SNL/KAFB is located along the eastern margin of the Albuquerque basin (Figures 3.1.1-1 and 3.1.1-2), a major structural feature of the central Rio Grande rift. The site is located on the western margin of the Manzanita Mountains and on the partially dissected, coalescent alluvial fan complex that flanks the mountain front to the west.

The Rio Grande rift is approximately 620 mi (1000 kilometers [km]) long and is one of the major structural features within the southwestern United States. The Albuquerque basin is one of a series of roughly north-south-trending, en echelon basins characterized by attenuated crust, elevated heat flow, recent faulting and volcanism, and thick basin fill. The basin is 90 mi (145 km) long, 31 mi (50 km) wide, and covers an area of 2723 square miles (mi^2) (7400 square kilometers [km^2]) (Woodward 1977, Lozinsky et al. 1991). The Albuquerque basin is an asymmetrical graben with over 32,800 ft (10,000 m) of structural relief adjacent to the Sandia uplift to the east, and only about 1150 ft (350 m) on the west side. It is bordered by basement uplifts on the east, including the Sandia, Manzanita, Manzano, and Los Piños uplifts. There are numerous synthetic and antithetic faults within the Albuquerque structural depression. Faults throughout the rift basin are interpreted as listric (i.e., flatten with depth) (Woodward 1977, Russell and Snelson 1994).

The north-trending Albuquerque basin underwent subsidence and about 5 mi (8 km) of northwest-southeast extension over the past 30 to 40 million years ago (Ma) (Woodward 1977, Lozinsky 1994). Deep seismic reflection data suggest that the basin is divided into two half-grabens bordered by major upper Tertiary faults (Russell and Snelson 1990, 1994). These grabens are separated by the northeast-trending Tijeras fault zone (see Attachment 1, Section 3.4.1.1), which acts as a zone of accommodation between the northern and southern subbasins. In this model, the basin is characterized as a deep, sediment-filled inner depression flanked by a series of faulted ramps along the basin margin. Upper Tertiary faults with the largest displacements border the inner structural trough (Chapin and Cather 1994); however, many faults within and bordering the basin exhibit evidence of late Pleistocene displacement. Overall structural relief between Precambrian rocks within the inner trough to the top of the eastern margin uplift is approximately 6 mi (10 km). The two graben structural model is still viable and is supported with extensive subsurface structural, stratigraphic, and geophysical investigations (Hawley and Haase 1992).

SNL/KAFB is located in a structurally complex area (Figures 3.1.1-3). A number of major regional faults intersect within the area resulting in a diverse pattern of fault trends and displacements. Based on these fault trends and displacements, the SNL/KAFB area has been subdivided into four hydrogeologic regions (SNL/NM 1993a, 1994a, 1995a): (1) a mountainous Manzanita Mountains area; (2) an eastern area of bedrock outcrops, representing uplifted terrain that exhibits fault displacements and fracture lineaments; (3) a middle area dominated by north- to south-trending, west-dipping normal faults interconnected in some cases by subdued graben features, and characterized by relatively shallow depth to bedrock; and (4) a western area dominated by thick alluvial fill and evidence of additional north- to south-trending, west-dipping faults that have produced a series of down-to-the-west bedrock steps. This report focuses on the latter three hydrogeologic regions because most HSWA sites are located within these three regions. The complexity of the fault-bounded regions necessitates separate discussions of these areas (see Attachment 1, Sections 3.1, 3.2, and 3.3 for more detailed discussion).

Knowledge of the SNL/KAFB structural fabric and framework is important to the ER Project staff in their efforts to reduce uncertainties related to potential contaminant flow paths within the vadose and saturated zones. Factors, such as determination of fault trends, assessments regarding their behavior as barriers to fluid flow or as seepage surfaces, and identification of movement in recent times, are important in risk-based assessment.

Several major rift-bounding faults are present on SNL/KAFB (Figure 3.1.1-3). These include north- and northeast-trending faults along the base of Manzano Base and the Manzanita Mountains (e.g., Sandia and Coyote faults) and faults located west of the range front (e.g., Hubbell Springs fault and unnamed faults west of the Hubbell Springs fault). They generally are west-dipping normal faults that exhibit down-to-the-west displacement. In addition, the northeast-trending Tijeras fault zone traverses SNL/KAFB and intersects or merges with the Sandia and Hubbell Springs faults in the south-central part of the site (Figure 3.1.1-3). The following discussion comments briefly on structural characteristics of each major fault on SNL/KAFB. The interpreted fault trends are based on aerial photograph studies, field investigations, geophysical information, and well data evaluations.

Sandia fault

The Sandia fault is a north- to northeast-trending, west-dipping normal fault along the eastern margin of the central Albuquerque basin (Kelley and Northrop 1975). The location and lateral continuity of the fault along its approximate 25 mi (40 km) length are poorly constrained. An exposure of the fault in Tijeras Arroyo (north of SNL/KAFB, at the mouth of Tijeras Canyon) documents the offset with Precambrian granitic rocks faulted against Pleistocene alluvial fan sediments. Kelley (1977) suggests late Quaternary displacement on the fault based on a topographic scarp along the Rincon fault, which is a northern extension of the Sandia fault 12 mi (19 km) to the north of SNL/KAFB (Cordell 1978). The southern extent of the Sandia fault is difficult to ascertain because it intersects or merges with the Tijeras fault zone and the Hubbell Springs fault (see Attachment 1, Sections 2.1.2 and 3.2.1).

Substantial increases in thicknesses of late Tertiary Santa Fe Group units occur west of the fault (Hawley and Haase 1992, May and Russell 1994). Subsurface geologic investigations along the west side of Manzano Base (SNL/NM 1994a, Section 5.4) support an interpretation of significant vertical offset on the Sandia fault. These subsurface investigations utilized several geophysical methods, including reflection seismic (Sigma 1984), surface gravity (Goodrich 1992), and controlled source audio frequency magnetotelluric surveys (CSAMT) (Bartel et al. 1981). These surveys documented a western fault strand with significant offset west of the widely recognized and mapped Sandia fault trace. Field investigations during 1995 further constrained the surface trace location of the Sandia fault along the west side of Manzano Base (see Attachment 1, Section 2.2.3).

Hubbell Springs fault

The Hubbell Springs fault is a series of north-trending, west-dipping normal fault strands along the western margin of the Hubbell structural bench, which extends to the south from the southeastern part of SNL/KAFB (Figure 3.1.1-3) for a distance of 36 mi (58 km) (Kelley 1977). The northern half of the fault is known for its freshwater springs. The fault intersects or merges with the Tijeras fault zone and the Sandia fault in the south-central part of SNL/KAFB along the northwest-trending graben. The intersection of the Hubbell Springs fault and the Tijeras fault zone at the northern end of the graben is coincident with the southern extent of bedrock outcrops of the Manzano Base uplift (Attachment 1, Sections 2.1.2.3 and 3.2.3).

A prominent fault scarp on the Isleta Pueblo exposes Paleozoic and possible Triassic bedrock along its length (Kelley 1982). Characterization of these outcrops is important in bedrock identification beneath the alluvium east of the fault complex on SNL/KAFB (Attachment 1, Sections 2.2.1 and 3.3.3). The Hubbell Springs fault also displays prominent geomorphic evidence of late Quaternary displacement and is a major potentially active fault in the eastern part of the Albuquerque basin. Although there is ample evidence for multiple fault movements during the Quaternary, surficial mapping shows no evidence for displacement of Holocene deposits (see Attachment 1, Section 2.1.2). In addition, observations of fault-scarp morphology by Machette (1982) do not support Holocene movement. Middle and late Pleistocene alluvial fan deposits are displaced along the northernmost part of the fault on SNL/KAFB. Possible fault-related features are present across these (see Attachment 1, Section 2.1) fan deposits, which are approximately 21,000 years (yr) old. These relations, supported by scarp morphology data collected along two segments of the Hubbell Springs fault (Machette 1982), suggest that the most recent movement along the southern part of the fault occurred during the late Pleistocene.

Tijeras fault zone

The Tijeras fault zone is a major structural feature cross-cutting the Rio Grande rift. The term "zone" in this situation refers to the presence of several anastomosing subparallel fault strands with extensively sheared rock material between them. Although always considered important in the past (Kelley 1977, 1982; Lisenbee et al. 1979; Russell and Snelson 1990), the fault zone received renewed prominence in recent publications on basins of the Rio Grande rift (Chapin and Cather 1994, Lewis and Baldridge 1994, May et al. 1994, May and Russell 1994, Russell and Snelson 1994). The fault zone extends some 58 mi (93 km) from central SNL/KAFB northeastward to the Cañoncito area within the Sangre de Cristo Mountains, approximately 14 mi (23 km) beyond the SNL/KAFB boundary (Figure 3.1.1-1). On SNL/KAFB, the Tijeras fault zone extends from an area southwest of Manzano Base where it intersects or merges with the Sandia and Hubbell Springs faults (see Attachment 1, Section 3.0) to the northeast through Tijeras Canyon, where it separates the Sandia and Manzanita Mountains (Figure 3.1.1-3).

The fault zone consists of several subparallel faults with near-vertical dips and normal and left-lateral displacements (Lisenbee et al. 1979, Maynard et al. 1991). There are multiple episodes of movement based on outcrop relationships along the fault trace on and northeast of SNL/KAFB. There is evidence that these episodes occurred during the Precambrian, Paleozoic, upper Tertiary, and Quaternary, with each episode having a different mode of displacement (Lisenbee et al. 1979, Abbott and Goodwin 1995). The fault zone has had as much as 1.5 mi (2.4 km) of left-lateral, post-Cretaceous offset (Kelley and Northrop 1975). On SNL/KAFB, the Tertiary through Quaternary sense of offset is difficult to ascertain, but appears to display variable senses of vertical displacement (Lozinsky et al. 1991). Upper Tertiary motion is consistent with the development of the Rio Grande rift (Abbott and

Goodwin 1995). Possible displacement of Quaternary colluvium in Tijeras Canyon (Lisenbee et al. 1979) is evidence for the fault zone being a potentially active structure. An exposure of the Tijeras fault in the Tijeras-Cañoncito area supports Quaternary offset where Quaternary(?) strata are juxtaposed against Oligocene(?) igneous rocks (Abbott and Goodwin 1995). Machette (1982) suggests that the Tijeras fault zone was active on SNL/KAFB and the Isleta Pueblo during the Holocene. Across-fault tonal contrasts along its trace east of Manzano Base, as noted on aerial photographs, suggest recent (late Quaternary or later) fault activity. Surficial deposit mapping on SNL/KAFB (Attachment 1, Section 2.1.2.2) confirms late Pleistocene displacement along the Tijeras fault south of the Travertine Hills, immediately southwest of Manzano Base. Recent shallow refraction seismic survey lines across the fault zone in the Arroyo del Coyote area do not indicate offset of the alluvium overlying bedrock (see Attachment 1, Section 3.2.2).

Coyote fault

The Coyote fault is a north- to northwest-striking fault located along the base of the Manzanita Mountains in the southeastern part of SNL/KAFB (Figure 3.1.1-3). The fault has an inferred length of 4.5 mi (7.2 km), but may extend further south (Reiche 1949, Kelley 1977).

The Coyote fault forms the eastern margin of the Hubbell structural bench and exhibits down-to-the-west composite displacement of about 1300 ft (396 m). The fault is expressed geomorphically as linear range-front facets, and, as evidenced by the coincidence of Coyote Springs with the Coyote fault, probably influences groundwater pathways between the range block and the Hubbell bench. Where the fault trace is exposed, bedding on the west side is dragged near vertical against Precambrian quartzite in the footwall. There are no available data addressing possible late Quaternary activity on this structural feature, although surficial mapping shows the presence of subtle, possible fault-related lineaments along the fault south of Coyote Springs and near South Fence Road.

Colorada fault

The Colorada fault was originally identified by Kelley (1977) as a northwest-trending, down-to-the-southwest fault in the southwestern portion of SNL/KAFB. Evidence of this fault is primarily an apparent 4 mi (6 km) northwest offset of the northern half of the Manzanita Mountains range front. Geologic mapping of bedrock units in the southwestern portion of SNL/KAFB and northern portion of the Isleta Pueblo (see Attachment 1, Section 2.2) provides corroborating circumstantial evidence for the presence of the Colorada fault. There is no evidence of middle to late Pleistocene displacement along the Colorada fault, based on surficial geologic investigations (see Attachment 1, Section 2.1).

Southwestern Sandia National Laboratories/Kirtland Air Force Base lineaments

The area between the Hubbell Springs fault and the eastern escarpment of the Rio Grande Valley contains several prominent north-trending air-photography lineaments and topographic scarps (SNL/NM 1994a) that coincide with an unnamed fault mapped by Hawley and Haase (1992). These potentially fault-related lineaments occur in a zone approximately 4 mi (7 km) wide that extends from Hells Canyon Wash to near McCormick Ranch, directly west of the western SNL/KAFB boundary (Figure 3.1.1-3). The overall pattern of the lineaments suggests a broad, complex graben containing several smaller-scale internal horsts and grabens (SNL/NM 1994a, Section 5.3.5.6). Surface geology activities conducted during 1994 provided additional information on these faults and possible fault-related lineaments (SNL/NM 1995a, Section A.2.3 and Plates III and IV).

3.1.2 Stratigraphic Setting

To understand fully how faults and, moreover, how sediments and bedrock are laterally and vertically distributed throughout the SNL/KAFB area, an understanding of the stratigraphic framework is of fundamental importance. This framework is important for the development of a geologic conceptual model and interpretation of the regional geologic history.

Only those stratigraphic units relevant to SNL/KAFB will be discussed in this report. Their lithologic characteristics, regional and local distributions, and water-bearing potential are addressed in the following discussions. Rock units are grouped into six major categories and described from oldest to youngest: (1) Precambrian basement complex, (2) upper Paleozoic strata, (3) lower Mesozoic strata, (4) lower Tertiary strata, (5) upper Tertiary/Quaternary Santa Fe Group strata, and (6) Quaternary post-Santa Fe Group sediments (upper Pleistocene to Recent). Additional information on the various formations and lithologies is available in summary descriptions in Kues et al. (1982) and from the specific references cited in the following sections.

3.1.2.1 Precambrian basement complex

Surface exposures of basement complex on SNL/KAFB consist of Precambrian igneous, metasedimentary, metaigneous, and other metamorphic rocks (Figure 3.1.2-1; see also Attachment 1, Plate II). Basement bedrock is exposed in the uplifted Manzano Base and Manzanita Mountains, located in the central and eastern part of SNL/KAFB, respectively (Myers and McKay 1970, 1976). West-facing mountain fronts, which are coincident with north- and northwest-trending faults, expose Precambrian granite, metarhyolite, greenstone, quartzite, and minor gneiss and schist. These rock types underlie late Paleozoic sediments throughout the western Manzanita Mountains, and are interpreted to underlie Paleozoic units on the Hubbell bench and in the basin to the west (see Attachment 1, Section 3.2.1.3). In many places, the basement complex is also in unconformable contact with overlying Albuquerque basin-fill deposits (i.e., Santa Fe Group) directly west of the mountain front uplifts. The subsurface unconformable relationship between the Precambrian complex and Pleistocene surficial deposits was documented by borehole drilling within Lurance Canyon (Foutz 1994) and along Arroyo del Coyote (see Attachment 1, Section 3.2.1.3).

For all practical purposes, the Precambrian complex has no primary porosity and very low specific yield and permeability. Faulting and jointing have created locally permeable zones through which water can move (Titus 1980). A number of springs and seeps discharge varying amounts of water from the Precambrian complex along the west face of the Sandia and Manzanita Mountains. Precambrian rocks in the SNL/KAFB area display many fractures, faults, and other deformational features and fabrics related to various episodes of tectonism. (Attachment 1, Section 2.2.2.2, contains a discussion of the preliminary fracture pattern investigations.)

Descriptions of the Precambrian geology of the Sandia, Manzanita, and Manzano Mountains adjacent to and within SNL/KAFB are provided by Reiche (1949), Myers and McKay (1970, 1971, 1976), Kelley and Northrop (1975), and Calvin et al. (1982). The following is a brief summary of the main Precambrian rock units known to occur on and near eastern SNL/KAFB.

Sandia granite

The Sandia granite is exposed at Manzano Base on SNL/KAFB, and is prevalent on the west uplifted escarpment of the Sandia Mountains (Reiche 1949; Myers and McKay 1970, 1976). Radiometric dating of the granite suggests emplacement at 1445 ± 40 Ma (Brookins 1982). According to Kelley and Northrop (1975) the granite is homogeneous throughout its exposures. The most distinctive characteristic of this quartz monzonite is its porphyritic texture: microcline phenocrysts in a granitoid groundmass of quartz, feldspars, and mica. The Sandia granite provides an important detrital constituent in clast assemblages and coarse matrix within the late Tertiary and Quaternary basin-fill alluvium of the east-central Albuquerque basin.

Cibola gneiss

The Cibola gneiss is bounded by the Tijeras fault to the southeast and the Sandia granite of Manzano Base to the northwest on SNL/KAFB (Calvin et al. 1982, Connolly 1982). It had been mapped as Precambrian "biotite granite" by Myers and McKay (1976). Several hypotheses have been proposed regarding the origin of the gneiss. Connolly (1982) considers the origin of this unit to be from metamorphosed arkose and cites the presence of quartzite lenses within the mapped unit. Other workers consider the gneiss to be a tectonized granitic zone associated with the granite of Manzano Base (Kirby and Karlstrom 1994). The overall fabric varies from weakly foliated to strongly gneissic, with grain size varying from fine to very coarse grain. Field evidence indicates that the gneiss was folded isoclinally about gently northeast-plunging fold axes, followed by tight refolding about northwest-plunging axes at high angles to the first folding (Connolly 1982). Radiometric dating of the Cibola gneiss indicates that the metamorphism took place 1576 ± 73 Ma (Brookins 1982).

Isleta metasediments

Isleta metasediments are present immediately south of SNL/KAFB, within the southern Manzanita Mountains (Calvin et al. 1982). This unit consists of phyllite, meta-arkose, and metaquartzite. Phyllites are tan to light green, and are composed of moderately to well-aligned, extremely fine-grained sericite and chlorite with angular clasts of quartz and feldspar. Although Isleta metasediment surface exposures are outside the SNL/KAFB boundary, detrital clasts eroded from this unit are present as a component of the basin-fill alluvium overlying the Precambrian complex.

Tijeras greenstone complex

The Tijeras greenstone complex (Reiche 1949, Calvin et al. 1982, Connolly et al. 1982) is present immediately southeast of the Tijeras fault, east of Manzano Base, where it is juxtaposed against Cibola gneiss. This complex consists of a thick series of chloritic greenschist-facies units of metaigneous origin. Massive greenstone is also exposed in the lower Hells Canyon area of the northern Manzano Mountains to the south of SNL/KAFB (Calvin et al. 1982). These greenstones provide a distinct detrital clast component to the basin-fill alluvium of the western part of SNL/KAFB.

Coyote Canyon sequence

The Coyote Canyon sequence, exposed in the Arroyo del Coyote area of SNL/KAFB, as described by Calvin et al. (1982), consists of the Cerro Pelon quartzite, an overlying unit of quartzite and phyllite, a thin quartzite, a wedge of felsic metavolcanics, and a unit of mafic to intermediate metavolcanics (equivalent to the Servillita metarhyolite) with interbedded metasediments. The quartzites are extremely pure (greater than 95% quartz) and provide an easily discernible clast type within the overall basin-fill alluvium clast assemblage.

3.1.2.2 Upper Paleozoic strata

A sequence of upper Paleozoic strata rests unconformably on a low-relief Precambrian erosion surface with an inferred 1.1 million-year (my) hiatus. The upper Paleozoic formations along the eastern margin of the central Albuquerque basin are middle Pennsylvanian to upper Permian in age and include interstratified carbonates and clastics of marine and nonmarine origin (Figure 3.1.2-1). Pennsylvanian-age rocks, prominently exposed in the Sandia and Manzanita Mountains, are subdivided into the Sandia Formation and overlying Madera Group (Figure 3.1.2-1). Permian strata include isolated Abo Formation outcrops on SNL/KAFB, and Abo, Yeso, Glorieta Sandstone, and possible San Andres Formation outcrops south of SNL/KAFB. Kelley and Northrop provide a comprehensive discussion of these stratigraphic units within the Sandia Mountains area (Kelley and Northrop 1975). Upper Paleozoic units significant to the understanding and interpretation of the SNL/KAFB hydrogeologic setting are discussed here in oldest to youngest stratigraphic order.

Sandia Formation

In the SNL/KAFB area, the lower middle Pennsylvanian Sandia Formation rests unconformably on a low-relief erosion surface developed on Precambrian rocks (Kelley and Northrop 1975, Myers 1982) (Figure 3.1.2-1). The Sandia Formation, in turn, is gradationally overlain by the Madera Group, which is marked by the presence of the first massive limestone bed. The Sandia Formation is a widely distributed unit with measured thickness variations from 10 to 230 ft (3 to 70 km) (Kelley 1963, Reiche 1949). On SNL/KAFB, it is exposed within the Manzanita Mountains and as outliers on the Hubbell bench.

Rock lithology within the Sandia Formation varies laterally. This dominantly siliceous clast unit consists of sandstone, shale, limestone, conglomerate, and siltstone (listed in decreasing abundances) (Kelley and Northrop 1975). The formation generally fines upward, with pebbly conglomerates occurring most commonly at the base and sandy limestones most commonly in the upper part. The conglomerates were derived from nearby Precambrian outcrops. The limestones are widely distributed and range from thin layers to dense, hackly, thick beds. Intervening sandstones are yellowish brown to light gray micaceous arkoses. Shale units are dark gray to black with interbedded coal seams and carbonaceous stringers.

Only a few springs discharge from the Sandia Formation (Titus 1980). On the basis of these few springs, limestone within this formation appears to have relatively high permeability values because of fractures and cavernous zones. In contrast, sandstone appears to have moderate permeability values.

Published lithologic descriptions of the Sandia Formation are from outcrop observations within the Sandia and Manzanita Mountains. Geologic investigations reported in this study (see Attachment 1, Section 3.2.1.2) encountered this unit in the subsurface at Arroyo del Coyote. This is the only known subsurface occurrence of this unit to date in the SNL/KAFB area.

Madera Group

The Madera Group is subdivided into the basal Los Moyos Formation, the middle Wild Cow Formation, and the capping Bursum Formation (Myers 1973, 1982) (Figure 3.1.2-1). The base of the

Los Moyos Formation is transitional and conformable with the Sandia Formation, and the Bursum Formation is either disconformable or gradational and transitional to the overlying Abo Formation. The lower two formations are middle to upper Pennsylvanian, and the upper unit is lowermost Permian. The lower two formations are present on SNL/KAFB, on the surface within the Manzanita Mountains in the subsurface on the Hubbell bench. Limestone units within this group are characteristically fossiliferous throughout, a diagnostic criterion often used to identify this formation in well cuttings.

Los Moyos Formation — The Los Moyos Formation is approximately 590 ft (180 m) thick (Myers 1973, 1982). The lower one-third of the unit is primarily a medium gray calcarenite with lenses and bands of "rusty-weathering" chert. The upper part of the unit is a somewhat more clastic medium to light gray, cherty calcarenite.

Wild Cow Formation — The Wild Cow Formation is approximately 620 ft (189 m) thick and has been subdivided into three members (Myers 1973, 1982). The lower unit has a basal clastic unit which is overlain by a succession of calcareous gray shale and nodular shale. The middle unit also has a basal, coarse, clastic unit (cross-bedded conglomerate, arkose, and sandstone) which in turn is overlain by a gray shale containing local lenses of sandstone and siltstone, and finally capped by a light olive-gray calcarenite. The upper member similarly has a coarse clastic base which is overlain by calcareous gray shale with interstratified red beds, arkosic cross-bedded sandstone and siltstone, and gray calcarenite; the uppermost portion coarsens into a grayish orange arkosic cross-bedded sandstone and pebble conglomerate.

Bursum Formation — The lower Permian Bursum Formation is approximately 164 ft (50 m) thick and is gradational with the underlying Wild Cow Formation (Myers 1973, 1982). The unit loses its identity along a northward trend where the red beds grade or thin laterally into gray shale and limestone, or are laterally replaced by the Abo Formation (Myers 1982).

The Madera Group is the principal aquifer over all of the eastern back slope of the Manzano Mountains and over more than half the eastern slope of the Sandia Mountains (Titus 1980). Solution-enlarged channels in limestone beds tend to be localized along fractures and bedding planes, and provide the observed permeability and porosity. Fractures and/or bedding plane separations within shales provide some additional permeability. There is little evidence that sandstones, even when fractured, provide significant conduits for water.

The formations of the Madera Group have been encountered in the subsurface of SNL/KAFB. Efforts to map the subcrop have utilized lithologic data from recently drilled SNL/NM SWHC Project monitoring wells (see Attachment 1, Section 3.2.1.2). Sufficient lithologic information was available to differentiate these formations successfully for mapping purposes. Cores recovered from these wells and down-hole video results provided important information on the steep structural dips and cavernous openings associated with fractures within the bedrock. This unit is an important aquifer in the shallow bedrock area east of the fault complex on SNL/KAFB.

Abo Formation

The lower Permian Abo Formation is between 700 and 900 ft (213 and 274 m) thick (Kelley and Northrop 1975). This unit lies disconformably on or with apparent conformity on the Madera Group (Figure 3.1.2-1). The top of the formation is represented by a sharp conformable contact with the overlying Yeso Formation. These two formations are difficult to differentiate on SNL/KAFB. They seem to lose their individuality in a northerly direction, with the last definable outcrops present along the Hubbell Springs fault scarp on the Isleta Pueblo, south of SNL/KAFB (Kelley 1977, 1982).

The Abo Formation consists of an alternating sequence dominated by reddish brown mudstone interstratified with lenticular, dark red to pink, locally light gray sandstone beds and by discontinuous beds of arkose, conglomerate, and pellet limestone (Kelley and Northrop 1975, Titus 1980). Sandstone beds are as much as 100 ft (30 m) thick and intervening mudstones are from 50 to 200 ft (15 to 61 m) thick. Unfossiliferous limestone and conglomerate are relatively rare and are generally restricted to the lower part of the Abo Formation.

Moderately permeable sandstone within the Abo Formation provides a source of water for wells in the Tijeras Canyon area (Titus 1980). Water production is enhanced by local faulting, fracturing, and folding of the strata.

Probable Abo Formation has been encountered in the subsurface of SNL/KAFB, east of the fault complex (see Attachment 1, Section 3.2.1.3). These subsurface data points are important in developing a bedrock subcrop map east of the fault complex on SNL/KAFB.

Yeso Formation

The lower Permian Yeso Formation gradationally overlies the Abo Formation (Figure 3.1.2-1). The Yeso Formation, approximately 500 ft (152 m) thick near the SNL/KAFB area (Kelley and Northrop 1975), is conformably or disconformably overlain by the Glorieta Sandstone. The nearest known exposures of this formation are to the south of SNL/KAFB, along the Hubbell Springs fault scarp on the Isleta Pueblo.

The Yeso Formation consists of tan-brown, well-sorted sandstone and light reddish or orange-brown siltstone and, in the middle portion of the unit, a light gray limestone (Kelley and Northrop 1975). Locally, discontinuous beds of gypsum or gypsiferous siltstone occur near the top of the unit. The clastic content becomes more arkosic and coarse grained to the north as the rocks become darker colored and less evaporitic (Baars 1961). The upper part of the Yeso Formation contains thick, even-bedded, tan-brown, light orange, and white fine- to medium-grained sandstones.

Sandstones within this formation are sufficiently permeable and have high enough porosity for sustained water production in wells within the Sandia and Manzano Mountain areas (Titus 1980). Several springs discharge water from various parts of the Yeso Formation.

The presence of Yeso Formation on SNL/KAFB is evidenced by wells drilled in the area east of the fault complex (see Attachment 1, Section 3.2.1.2). Wells drilled along the southern border of SNL/KAFB encountered reddish brown siltstones with common occurrences of gypsum, which are interpreted to be Yeso Formation (SNL/NM 1994a). As stated in the section on the Abo Formation, the Yeso and Abo Formations cannot be differentiated in the northerly direction. The last discernible Yeso outcrops are on the Hubbell bench within the Isleta Pueblo (Kelley 1977, 1982).

Glorieta Sandstone

The upper Permian Glorieta Sandstone varies in thickness from 65 to 125 ft (20 to 38 m) (Kelley and Northrop 1975). It rests conformably or disconformably on the Yeso Formation along an abrupt contact (Figure 3.1.2-1). Sandstone outcrops along the eastern side of the Sandia Mountains form prominent ridges because of their resistance to erosion. The unit is a well-sorted, white, fine- to medium-grained, siliceous sandstone commonly cemented with carbonate (Baars 1961, Titus 1980). Water-bearing formation sandstones are most likely a result of fracture flow, because of the generally well-cemented nature of the strata.

The sandstone was encountered in monitoring wells drilled along the southern boundary of SNL/KAFB (see Attachment 1, Section 3.2.1.2). The Glorieta Formation is exposed in outcrops on the Hubbell bench within the Isleta Pueblo based on field work conducted there for this report.

San Andres Formation

The San Andres Formation is the uppermost Permian unit in the central Albuquerque basin area. Although it is described in outcrop along the Sandia Mountains, the only known locality near SNL/KAFB is on the Isleta Pueblo, south of the KAFB boundary. Regionally, the San Andres Formation is disconformably overlain by the Bernal Formation. The unit is up to 190 ft (58 m) thick and consists of gray to black, very fine to fine-grained limestone with some interstratified sandstone similar to the underlying Glorieta Sandstone (Kelley and Northrop 1975, Titus 1980). The limestone is thin to medium bedded and locally cavernous. The hydrologic significance of the solution features is that the San Andres Formation may be cavernous to great depths where present in the subsurface (Titus 1980). The cavernous nature was most likely formed during extensive periods of exposure during the Triassic prior to burial by the overlying Santa Rosa Formation. The high permeability and cavernous nature is not, however, pervasive throughout.

Exposures of the San Andres Formation on the Isleta Pueblo are limited to a location at the northern part of the Hubbell Springs fault scarp. To date, this formation has not been identified on SNL/KAFB either on the surface or in the subsurface.

3.1.2.3 Lower Mesozoic strata

The upper Triassic Santa Rosa Sandstone (Figure 3.1.2-1) rests unconformably on the San Andres Formation in the Sandia Mountains. The structural and stratigraphic relationships of this sandstone with the lower Tertiary in the SNL/KAFB area are unknown. The apparent 150 Ma hiatus is partially represented by major late Cretaceous to early Tertiary tectonism (Martinez 1989). The Santa Rosa Sandstone typically consists of light gray to reddish brown, lenticular sandstone and reddish brown shale (Titus 1980). Where present in the subsurface, the sandstone is typically an aquifer. Primary porosity within sandstone beds, and possible secondary porosity formed by fractures, provide water storage.

The Santa Rosa Sandstone presence near SNL/KAFB is limited to the Isleta Pueblo, south of KAFB. The only exposures known in the vicinity of SNL/KAFB are on the Hubbell bench within the Isleta Pueblo (Hawley 1995). At this location, the Santa Rosa Sandstone rests in apparent disconformity on the upper Permian Glorieta Sandstone. The Santa Rosa Sandstone occurs in these exposures as a tan-brown sandstone with abundant petrified wood. At the writing of this report, the Santa Rosa Sandstone has not been noted either in outcrop or in the subsurface of SNL/KAFB.

3.1.2.4 Lower Tertiary strata

Although no lower Tertiary-age strata outcrop on SNL/KAFB, they occur as subsurface units within the central and western parts of the Albuquerque basin (Lozinsky 1994). Their importance and relevance to this geologic investigation is limited to the northernmost Hubbell bench. Two lower Tertiary units are discussed in this report: the Baca/Galisteo Formations and the Unit of Isleta #2 Well. These units were encountered in the subsurface along the southern boundary of SNL/KAFB.

Baca/Galisteo Formations

The Eocene Baca and Galisteo Formations are lithologically similar and depositionally time-synchronous in New Mexico (Lucas 1982). They lie unconformably on Mesozoic strata (Figure 3.1.2-1) and are as much as 1640 ft (500 m) thick in the central Albuquerque basin. In the central basin, the two formations are virtually indistinguishable. These units are dominantly fluvial in nature and were deposited in two main shallow pre-rift basins within the central New Mexico area (Cather and Johnson 1984). Lithologically they are characterized by purplish red to gray, well-indurated, poorly to moderately sorted, fine- to coarse-grained sandstone with claystone and silty sandstone interbeds (Lozinsky 1994). In addition to the flüvial deposits, Russell and Snelson (1994) reported some organic-rich lacustrine deposits but did not identify where they occur. The Baca/Galisteo Formations do contain water but are not known to be commonly used for water supply in the SNL/KAFB area (Titus 1980).

Lower Tertiary strata, consisting of greenish gray to dark gray sandstone, siltstone, shale, and coaly shale, were encountered in a down-faulted structural block at the southern border of SNL/KAFB (see SNL/NM 1994a, Section 5.5.4.2). The age was confirmed by palynological analyses of several core samples from South Fence Road wells (MICROPALEO 1993; see also Attachment 1, Section 3.2.1.2). These strata are most likely equivalent to the lacustrine deposits mentioned by Russell and Snelson (1994).

Unit of Isleta #2 well

Lozinsky (1988, 1994) described an ash-dated Oligocene sequence of pinkish red to brown, weakly consolidated, poorly to moderately sorted, fine- to coarse-grained sand with clay and silt interbeds from the Shell, Isleta #2 exploratory well, approximately 10 mi (16 km) west-southwest of SNL/KAFB. This unit lies in apparent conformity on the underlying Baca/Galisteo Formations (Figure 3.1.2-1). As indicated above, this interval contains interbeds of silicic to intermediate volcanic flows and tuffs. It is up to 7000 ft (2134 m) thick in the central part of the Albuquerque basin but, similar to the underlying Baca/Galisteo Formations, thins rapidly to the eastern margin of the basin (Lozinsky 1994).

An equivalent-aged unit may overlie the Baca/Galisteo Formations strata in the down-faulted structural blocks (mentioned in the Baca/Galisteo Formations section) (SNL/NM 1994a, Section 5.5.4.2). These strata also are restricted to the southernmost part of SNL/KAFB. The correlation is based largely on stratigraphic position. Lithologically, the strata within the down-faulted blocks are light pinkish gray to greenish gray, weakly consolidated, fine- to very fine-grained sandstones, siltstones, and silty claystones.

Section 3.2.12 of Attachment 1 contains a discussion of the relationship of these lower Tertiary strata to stratigraphically overlying and underlying units. The distribution of this lower Tertiary strata is structurally controlled on the east and west by north-south bounding faults. This unit appears to have laterally extensive permeable sandstone units, lacks the level of induration of the underlying Paleozoic deposits, and occurs at shallow depths (35 to 400 ft [11 to 122 m]) in the area within and east of the fault complex. Therefore its identification, distribution, and characterization is important for modeling efforts within the vadose and saturated zones in the south-central portion of SNL/KAFB.

3.1.2.5 Upper Tertiary Santa Fe Group strata

Santa Fe Group strata comprise the principal syn-rift fill of the Albuquerque basin. This stratigraphic unit has been studied by many investigators since the early 1900s. The Santa Fe Group consists of complexly interstratified gravels, sands, silts, and clays representing basin filling synchronous with basin rifting between approximately 30 and 5 Ma (Figure 3.1.2-1). These sediments were deposited as alluvial fans derived from the nearby mountains, as sediments transported by rivers from source areas outside the basin, or as locally thick playa-lake and eolian deposits (Kelley 1977, Lozinsky 1988, Ingersoll et al. 1990, Hawley and Haase 1992). Buried soil horizons are common within these sediments. The Santa Fe Group is over 14,500 ft (4421 m) thick in the center of the rift, which is located near the western margin of SNL/KAFB.

Initial deposition of the Santa Fe Group was coincident with the early rifting of the Albuquerque basin portion of the Rio Grande rift. Contact of basal Santa Fe Group and underlying strata varies from conformable to unconformable depending on the area relative position along the basin margin. The upper contact boundary of the Santa Fe Group is difficult to identify because it is defined as being associated with the time of Rio Grande entrenchment into the youngest group sediments. Identification of this upper contact is particularly difficult along the rift basin margins where SNL/KAFB is located, because of the subtle nature of the depositional changes near the mountain fronts. Therefore, identification of this contact in the SNL/KAFB area is not stressed in this geologic investigation.

There is a diverse stratigraphic subdivision of this group noted in the literature (Kelley 1977). Because the lithologic nature of the Santa Fe Group was controlled by local depositional settings, past investigations defined subunits that were specific to distinct geographic areas (Bryan and McCann 1937, Galusha 1966, Lozinsky and Tedford 1991, Spiegal and Baldwin 1963, and Tedford 1982). Because of this stratigraphic diversity, only those subdivisions specific to the SNL/KAFB area will be discussed in this geologic investigation.

Lozinsky (1994) subdivided the Santa Fe Group into two major units, based on the regional Albuquerque basin history. Thorn et al. (1993) adopted a three-way subdivision of the Santa Fe Group for their hydrologic computer modeling efforts for the City of Albuquerque. Hawley and Haase (1992) subdivided the group into three major hydrostratigraphic units based on depositional environments and age (Figure 3.1.2-1). Hawley and Haase (1992) further differentiated the Santa Fe Group into ten lithofacies on the basis of sediment texture, the degree of induration, the geometry of bodies of a given textural class, and the distribution pattern of contrasting textural zones. These lithofacies are discussed and compared to units defined within the SNL/KAFB area in Attachment 1, Section 3.1.1.2.

Significant modification of Hawley and Haase (1992) was necessary for the SNL/KAFB study. Their study was based on a regional investigation of the Albuquerque basin-fill sediments. SNL/KAFB is located astride the eastern margin of the rift, and includes areas of erosion (the Manzanita Mountains), transport (the Hubbell bench), and deposition (the Albuquerque basin). At SNL/KAFB, the basin-fill sedimentation history was directly controlled by the uplifted areas to the east. Rates of sedimentation were dictated by paleoclimatic conditions, effects of eastern mountain-front uplift, and the degree of through-flowing ancestral Rio Grande dominance as an aggradational source. Because the

Hawley and Haase (1992) study is the most comprehensive report applicable to the SNL/KAFB area, Section 3.1.1.2 of Attachment 1 provides a correlation with that work.

The stratigraphic subdivision interpreted by Hawley and Haase (1992) is discussed in more detail herein because their study includes the SNL/KAFB area as well as adjacent areas to the west and north. The subunit thicknesses are highly variable, being thickest in the center of the basin and thinnest along its margin.

Lower Santa Fe unit

The lower Santa Fe hydrostratigraphic unit is dominated by interfingered piedmont-slope alluvial fan deposits, eolian, and fine-grained basin-floor deposits (Hawley and Haase 1992). The unit ranges in age from approximately 30 to 15 Ma (late Oligocene to middle Miocene) and represents deposition in an internally drained basin prior to deep subsidence and uplift of the rift-margin ranges. This stratigraphic unit is up to 3500 ft (1070 m) thick and grades laterally from fine clastic sediments in the basin center to the conglomeratic sandstones at the basin margin. This unit, at present, is not known to form a major part of the Albuquerque basin aquifer system.

Middle Santa Fe unit

The middle Santa Fe hydrostratigraphic unit was deposited between approximately 15 and 5 Ma (middle to late Miocene) when rift tectonism was most active. This is the thickest of the three Santa Fe Group units and was formed by rapid sedimentation related to the active tectonism. Sedimentation rates for the center of the basin have been calculated as high as 1968 ft/my (600 m/my) by Lozinsky (1994). The overall depositional environments were similar to those of the lower Santa Fe Group unit: primarily alluvial, eolian, and playa-lake. Hawley and Haase divide this 10,000-ft (3049-m) thick unit into two subunits based on sediment source terranes (Hawley and Haase 1992). Piedmont-slope sediments continued to be deposited at the margins of the Albuquerque basin. Coarse-grained alluvial fan deposits derived from the ancestral Sandia, Manzanita, and Manzano uplifts interfinger basinward with sandy to fine-grained basin-floor facies, which include local braided stream and playa-lake facies. Unlike the lower Santa Fe depositional settings, major fluvial systems from the Colorado Plateau and southern Rocky Mountain provinces to the north and the Rio Grande rift basins to the northeast were transporting sediments into the basin, forming a separate subunit. This unit was comprised of sandy to fine-grained basin-floor sediments that intertongue with the piedmont-slope deposits, resulting in an interstratification of these two subunits. These systems probably terminated in playa-lakes in the southern part of the basin (Lozinsky and Tedford 1991). The middle Santa Fe unit forms a major part of the basin-fill aquifer system in the northern part of the Albuquerque basin but only a minor portion of the aquifer system in the SNL/KAFB vicinity.

Upper Santa Fe unit

The upper Santa Fe hydrostratigraphic unit was deposited from approximately 5 to 1 Ma (Pliocene to early Pleistocene) and possibly as late as 0.5 Ma (middle Pleistocene). Hawley and Haase (1992) divided this 1200-ft- (366-m-) thick unit into three subunits based on sediment source terranes. Two of these subunits are significant parts of the stratigraphic framework within the eastern Albuquerque basin area. One subunit associated with the SNL/KAFB area contains coarse-grained, alluvial fan and piedmont-veneer facies extending westward from the bases of the Sandia, Manzanita, and Manzano uplifts. This facies is characterized by poorly sorted, weakly stratified sand and conglomerate with an abundant silt and clay matrix. It is interstratified with a second subunit that includes cross-stratified, thick, clean sand and pebbly gravel deposits of the ancestral Rio Grande. Approximately 5 Ma, the Rio Grande established a through-flowing river system (Lozinsky et al. 1991), forming a large aggradational plain in the central basin area. Fine- to medium-grained overbank sediments were deposited in areas where major river systems merged, and in basin-floor and piedmont-slope transition zones. Interfingering of these two subunits has been documented in the SNL/KAFB area west of the fault complex (see Attachment 1, Section 3.1.1.3).

Differentiation of the two subunits is, in part, based on the presence of river-borne volcanic detritus in the ancestral Rio Grande facies. These deposits were derived, in part, from basalts, andesites, rhyolite flows, and pyroclastic units. The upper Santa Fe Group unit forms the lower part of the shallow aquifer below river-floodplain areas, and the upper part of basin-fill aquifers in the western part of the northeast and southeast Albuquerque well fields. Section 3.1.1 of Attachment 1 discusses the definition, description, and distribution within the Santa Fe Group west of the fault complex and shows that alluvial fan and ancestral Rio Grande deposits are interstratified within the upper Santa Fe Group.

3.1.2.6 Quaternary post-Santa Fe Group sediments

Post-Santa Fe Group units include alluvial fan, fluvial, eolian, playa, colluvial, and floodplain deposits (Lambert 1968, Hawley and Haase 1992, and Attachment 1, Section 2.1). These sediments reflect deposition in the area between the Manzanita Mountains and the Rio Grande after the most recent period of down-cutting of the Rio Grande and partial backfilling episodes. These episodes occurred approximately 0.5 to 1 Ma (Wells et al. 1987, Lozinsky 1994), and may be related to Quaternary glacial-interglacial cycles. These episodes are evidenced by a number of inset terraces along the Rio Grande (Lambert 1968, Hawley and Love 1991). For the past 10,000 to 15,000 yr, the basinal areas have aggraded because of a relatively high rate of sedimentation compared to the ability of Holocene drainages to remove the sediments.

Multiple alluvial fans are present throughout much of SNL/KAFB and are derived from the Manzano Base and Manzanita Mountain ranges and mountainous drainages. Discontinuous fluvial terraces are inset into older alluvial fans along major drainages and interfinger with younger alluvial fans. Eolian deposits include active and stabilized dunes, as well as eolian sheets that cover and modify alluvial deposits. Colluvium is present within the steep terrain of the mountains, and playa deposits are present in topographic and structural depressions in westernmost SNL/KAFB. Buried soils are common within many of these surficial deposits.

The distribution of these geomorphically related surficial deposits was documented in the 1993 SWHC Project Annual Report on surficial geologic maps (SNL/NM 1994a, Plates I and II) and the deposits were defined and described (SNL/NM 1994a, Section 5.3). Revised and updated versions of these two plates were included in the 1994 SWHC Project Annual Report (SNL/NM 1995a, Plates III and IV). The surficial deposits were mapped and discussed in more detail for the Tijeras Arroyo area, Arroyo del Coyote area, South Fence Road area, and McCormick Ranch area (SNL/NM 1995a, Appendix A). Section 2.1 of Attachment 1 provides additional revisions and synthesis of recently developed data.

3.1.3 Geomorphology

SNL/KAFB encompasses parts of four distinct geomorphic provinces shown on Figure 3.1.3-1: the Rio Grande, Llano de Manzano, Llano de Sandia, and Rift-Margin Ranges (Machette 1978). Each province contains distinct variations in geomorphic landforms, depositional environments, and types of bedrock between the Rio Grande Valley and the western slopes of the Sandia and Manzanita Mountains. The Rio Grande geomorphic province encompasses the Rio Grande Valley, which contains broad floodplain and stream channel alluvium deposited by the Rio Grande. The Llano de Sandia and Llano de Manzano geomorphic provinces (Machette 1978) are broad piedmonts between the Rio Grande Valley to the west and the Sandia and Manzanita Mountains to the east. The piedmonts are composed primarily of alluvial-fan deposits shed from the flanks of the adjacent mountains. The Sandia and Manzanita Mountains are grouped within the Rift-Margin Ranges geomorphic province and contain alluvial deposits within intermontane drainages and colluvial deposits on interfluve slopes. Each of the four geomorphic provinces is subdivided into several subprovinces (Figure 3.1.3-1) on the basis of the number and types of landforms, the source of surficial deposits, and types of surficial processes. Brief summary descriptions of each subprovince are provided below. Attachment 1, Section 2.1.3, provides additional information on surficial deposits in parts of selected subprovinces.

The Llano de Manzano geomorphic province includes the Upper Llano de Manzano and McCormick Ranch subprovinces (Figure 3.1.3-1). The Upper Llano de Manzano subprovince encompasses the broad, west-sloping piedmont along the western margin of the Manzanita Mountains. Alluvial fan sediments in this subprovince are derived from metamorphic and sedimentary rocks in the Manzanita Mountains (Figure 3.1.3-2). The McCormick Ranch subprovince, located west of the Upper Llano de Manzano subprovince, is a flat area containing numerous closed depressions and is dominated by eolian deposits derived from upper Santa Fe Group sediments and the Rio Grande Valley.

The Llano de Sandia geomorphic province includes the Tijeras Arroyo and Eldorado subprovinces (Figure 3.1.3-1). The Tijeras Arroyo subprovince contains the modern Tijeras Arroyo and alluvial-fan deposits formed by the ancestral Tijeras Arroyo (Figure 3.1.3-2). Surficial deposits derived from the Tijeras Arroyo drainage contain granitic and sedimentary clasts from the Sandia Mountains and sedimentary and metamorphic clasts from the Manzanita Mountains. The Eldorado subprovince is a moderately dissected piedmont containing coalescent alluvial fans derived from the western escarpment of the Sandia Mountains. Surficial deposits in this subprovince contain primarily granitic clasts from the Sandia Mountains.

The Rio Grande geomorphic province is not divided into subprovinces and consists primarily of the Rio Grande Valley floor (Figure 3.1.3-1). The Rio Grande province contains floodplain and terrace sediments deposited by the Rio Grande. These deposits are distinct from deposits in other subprovinces in the SNL/KAFB area because they are derived from many volcanic, igneous, metamorphic, and sedimentary rock sources in the upper drainage area of the Rio Grande in northern New Mexico and southern Colorado.

The Rift-Margin Ranges geomorphic province includes the Manzano Base (Four Hills), Manzanita Mountains, and Sandia Mountains subprovinces (Figure 3.1.3-1). These subprovinces are characterized by substantial topographic relief and narrow alluviated valleys. The Manzanita Mountains subprovince includes the headwaters of Arroyo del Coyote and smaller ephemeral drainages, and contains surficial deposits derived from the metamorphic and sedimentary rocks in the Manzanita Mountains. The Sandia Mountains subprovince includes the headwaters of drainages in the Eldorado subprovince and contains surficial deposits derived from granitic rocks in the Sandia Mountains. The Manzano Base (Four Hills) subprovince includes a series of four northeast-trending granitic hills surrounded by a moderately dissected piedmont. Surficial deposits within the Manzano Base (Four Hills) subprovince are derived from granitic rocks within Manzano Base.

3.1.4 Soil Stratigraphy

This section addresses the general characteristics of soils developed on surficial deposits on SNL/KAFB. For the purposes of the surficial-deposit characterization on SNL/KAFB, the term "soil" refers to a natural body of layers or horizons of mineral and/organic constituents of variable thicknesses, which differ from the parent material in their morphological, physical, and mineralogical properties and their biological characteristics (Birkeland 1984). In a soil, as used herein, at least some of these properties are a result of pedogenesis, which is the process of surficial weathering. This definition of soil is different from that used by engineers, in which soil is unconsolidated material, and from that used by soil scientists, in which soil is a medium for plant growth. The definition of soil used herein is helpful for the purposes of developing a hydrogeologic conceptual model for SNL/KAFB because: (1) soil descriptions using standard soil-survey nomenclature and methods provide information on the likely available water capacity of near-surface materials, on possible infiltration rates, and on thicknesses of horizons that may influence the direction and rate of groundwater flow; and (2) the previous soil survey (Hacker 1977) is based on this definition of soil. Soils as defined herein are also used to help correlate deposits throughout SNL/KAFB and provide information on the infiltration capacity of deposits.

3.1.4.1 Soil properties important to hydrogeologic characterization

Because the process of soil development alters the physical characteristics of surficial deposits, several soil properties may influence the rate and locations of groundwater flow. Most soil profiles can be divided into several prominent or master horizons, which are designated by capital letters such as A, B, K, C, or R (Birkeland 1984, Soil Survey Staff 1992). In arid and semiarid climates such as central New Mexico, surface or near-surface horizons typically are designated A horizons, which are relatively high in organic material compared to underlying horizons. The A horizon commonly has a substantial component of eolian material, and may be leached of soluble salts. The B horizon commonly is beneath the surface A horizon or horizons, and encompasses a multitude of soil characteristics that differ from those of the original parent material. Among B horizon characteristics are production of red colors and accumulation of secondary clay, iron compounds, and calcium carbonate ($CaCO_3$) or other soluble salts (Birkeland 1984). Lower-case suffixes commonly used to describe these B horizons include "-w" for slight reddening or development of soil structure (a cambic or Bw horizon), "-t" for substantial translocation of clay (an argillic or Bt soil horizon), and "-k" for accumulation of secondary $CaCO_3$ (a calcic or Bk horizon). These horizons represent potentially significant alterations of the original deposit.

The K horizon in a soil profile reflects prominent layers of $CaCO_3$ accumulation (Gile et al. 1965) and allows for the differentiation of weak calcic horizons, such as Bk horizons, from moderate to strong K horizons (Machette 1982). The K horizon must have more than 90% K-fabric, in which "...fine-grained authigenic carbonate occurs as an essentially continuous medium. It coats or engulfs, and commonly separates and cements skeletal pebbles, sand, and silt grains..." (Gile et al. 1965, p. 74). Because secondary $CaCO_3$ accumulates in a soil progressively through time, the description of a calcic soil horizon is facilitated by identifying the stage of $CaCO_3$ morphology (Machette 1982). The morphology of $CaCO_3$ in a soil depends on the original gravel content of the parent material. In deposits with high gravel contents, Stage I carbonate morphology has thin, discontinuous coatings of $CaCO_3$ on pebbles. In coarse-grained deposits, Stages II and III have progressively thicker and more continuous coatings (see Attachment 1, Appendix D for a complete description). Stages IV, V, and VI have thin to thick laminae of $CaCO_3$ and are indurated. These three stages denote K horizons, which are pedogenic calcretes, or "caliche" in colloquial nomenclature. Stage I carbonate morphology in fine-grained deposits consists of few filaments of $CaCO_3$, and Stages II and III have progressively larger and better indurated $CaCO_3$ nodules (Attachment 1, Appendix D). Stages IV, V, and VI carbonate morphology for fine-grained deposits have similar characteristics as those for coarse-grained deposits.

The C horizon represents unconsolidated, unweathered parent material that shows no evidence of pedogenesis (Birkeland 1984, Soil Survey Staff 1992). If a deposit is oxidized, it may be designated by the suffix "-ox" (Birkeland 1984). In soil investigations at SNL/KAFB, the designation "Cm" is used for horizons containing nonpedogenic cemented alluvium. The R horizon represents consolidated bedrock underlying soil.

Figure 3.1.4-1 illustrates important soil characteristics with an example of a moderately developed soil exposed in soil pit SP24 in south-central SNL/KAFB. This soil has a thin A horizon consisting primarily of reworked alluvium and eolian sand and silt. This horizon probably is very permeable to the downward percolation of water. Beneath the A horizon is a Bw horizon characterized by weak soil structure and a slight color reddening (Attachment 1, Appendix D). The absence of secondary $CaCO_3$ in this horizon suggests that the average depth of wetting at this site is less than approximately 15 inches (in.) (39 centimeters [cm]), which is the base of this horizon. Below the Bw horizon is a moderately developed Btk horizon that contains evidence of secondary carbonate and clay accumulation (Figure 3.1.4-1). This horizon has some color reddening (Munsell color of 7.5YR 5/6), and thin, discontinuous clay films that formed from translocation of material from overlying deposits. Laboratory data (Figure 3.1.4-1b) show that this horizon has substantially greater amounts of silt and clay than the adjacent horizons, which is consistent with the field observation of clay films. Beneath the Btk horizon are several Bk horizons that exhibit evidence of secondary accumulation of $CaCO_3$. The amount of $CaCO_3$ decreases from this horizon downward (Figure 3.1.4-1b), illustrating that the Bk1 horizon from 27 to 39 in. (69 to 99 cm) is the zone of greatest precipitation of pedogenic carbonate. Transport of soluble carbonate salts in solution typically only occurs as deep as approximately 40 in., although depths of percolation may occasionally reach approximately 80 in. (200 cm). The lowermost Bk horizon (3Bk on Figure 3.1.4-1) contains approximately 7 wt.% $CaCO_3$, which probably mostly reflects the original amount of $CaCO_3$ in the parent material. Thus, the average depth of infiltration at this site, over geologic time scales, is probably less than approximately 80 in. (200 cm). Because it is developed in a laterally extensive alluvial-fan deposit, this soil probably impedes downward-percolating water over large areas.

Several animal burrows, known as krotovina, were exposed at soil pit SP24 (Figure 3.1.4-1). Two sets of krotovina are present, showing two episodes of bioturbation. Because the near-vertical burrows are extensive and disturb the relatively impermeable soil horizons, downward-percolating water may follow these relatively permeable conduits as infiltration pathways into the deeper subsurface. Because the locations and orientations of krotovina are difficult to identify over large areas without extensive studies, the presence of these zones of disturbance may complicate vadose-zone modeling efforts.

3.1.4.2 General soil characteristics on Sandia National Laboratories/Kirtland Air Force Base

Before this investigation, no detailed soils study had been conducted throughout SNL/KAFB. The previous soil survey (Hacker 1977), which provides general characteristics of soils based on interpretation of aerial photography and a few shallow excavations into selected surficial deposits, was used for identification of vadose-zone hydrogeologic settings (Parsons et al. 1993). Surficial mapping conducted in 1993 and 1994 for the SWHC Project lacked additional information on soil characteristics, but provided an updated analysis of the distribution of surficial deposits based on analysis of aerial photography and field mapping (SNL/NM 1994a, 1995a). General characteristics of soils within the geomorphic subprovinces on SNL/KAFB (Figure 3.1.3-1) are provided in Section 4.1.3.2 of the 1993 SWHC Annual Report (SNL/NM 1994a).

The soil stratigraphy on SNL/KAFB is complex, with many factors interacting over the past several thousand to hundreds of thousands of years to produce the present-day soil properties. First, surficial soils on SNL/KAFB generally exhibit progressively greater soil development on progressively older deposits. The degree of soil development is dependent on the length of time the surface deposit is exposed to weathering and, therefore, can be used as a relative indicator of age. The temporal changes in soil properties thus allow for the correlation of deposits throughout SNL/KAFB. Pleistocene deposits typically have moderately to well-developed calcic horizons within 5 or 6 ft of the surface. In contrast, Holocene deposits generally lack calcic horizons. Development of calcic horizons is strongly dependent on the depth and rate of near-surface infiltration, and thus reflects the long-term average depth of wetting.

Second, many soil profiles contain evidence of abundant bioturbation, or the disruption of near-surface deposits by burrowing animals (Figure 3.1.4-1). This disruption influences infiltration rates by providing near-surface pathways for vertical water migration. Some soils exhibit evidence of burrowing followed by soil development, suggesting that the progressive bioturbation has been occurring for at least several thousand years. The presence of relatively high amounts of secondary clay minerals associated with some bioturbated horizons also suggests that bioturbation may promote increased drainage and weathering.

Third, the upper parts of almost all soils include eolian sand and silt, demonstrating that eolian deposition is an active and long-lived characteristic of the SNL/KAFB area. Virtually every soil profile exposed in the soil characterization program contains a significant component of eolian material at the surface. In many profiles, the eolian material overlies the remnants of an eroded soil profile, in which only the lower parts of a once moderately or well-developed soil profile are present. It is likely that wind and slopewash erosion have been active processes over much of the SNL/KAFB area. Because eolian deposits are present throughout SNL/KAFB, and therefore underlie nearly every ER site, characterizing the texture and geochemistry of the eolian deposits may be important to assessing background levels of constituents of concern and the presence or absence of manmade substances.

Fourth, original parent materials for the soils strongly influence the characteristics of soil profiles on SNL/KAFB. The majority of the soil profiles documented in this study are developed in alluvium containing clasts of many rock types, including granite, limestone, greenstone, quartzite, and sandstone. Several soils also are developed in eolian sand and silt. Of particular note is the presence of alluvium derived from granitic rocks within the Manzano Base (Four Hills) geomorphic subprovince. Soils developed in this granitic alluvium appear to be well drained, and tend to have wetting depths that are greater than soils developed in other parent materials. In addition, soils developed in alluvium containing limestone clasts are strongly influenced by the amounts of primary $CaCO_3$. As might be expected, these soils tend to have greater amounts of secondary $CaCO_3$ than those developed in alluvium or eolian deposits that lack limestone clasts. Undoubtedly, the type of parent material also strongly influences the geochemistry of the soils and percolating waters.

In conclusion, surface soils within SNL/KAFB are developed in fluvial, alluvial-fan, colluvial, and eolian surficial deposits. Variations in soil properties in these deposits reflect differences in sediment characteristics, in length of exposure to surficial weathering, and in local climate. Surficial geologic activities add additional detail for soils characterization on SNL/KAFB, update the delineation of near-surface alluvial deposits, and provide a means to improve the accuracy of the boundaries and distribution of vadose-zone hydrogeologic settings on SNL/KAFB. These activities provide a framework for future quantitative assessments of soil and near-surface hydrologic characteristics throughout SNL/KAFB, including vadose-zone hydrogeology, surface hydrology, and background geochemistry.

3.2 HYDROLOGY

This section provides a summary description of the current state of knowledge of the SNL/KAFB hydrologic setting. This summary description is a synthesis of information obtained from various hydrogeologic reports, SNL/NM ER Project investigations, and ongoing SWHC projects. The hydrologic setting is interrelated with the local geologic framework (see Section 3.1) and includes the meteorological environment (precipitation and evapotranspiration), surface-water runoff and infiltration, percolation through the unsaturated (vadose) zone, and saturated groundwater flow (Figure 3.2-1). The objective of this section is to summarize current understanding regarding the occurrence, movement, and interaction of surface and subsurface water on and under the SNL/KAFB area. This understanding is used to update the hydrogeologic conceptual model discussed in Section 4.0.

3.2.1 Meteorology

Local climatic conditions play a major role in the overall hydrologic setting for the SNL/KAFB area. SNL/KAFB is located on an alluvial plain on the eastern slopes of the Rio Grande Valley. The climate is typical of a high desert plateau with low precipitation, wide temperature extremes, and typically clear, sunny days. Average temperatures and winds are summarized in Figure 3.2.1-1.

The average precipitation at Albuquerque International Airport (at the northwestern corner of KAFB, elevation 5311 ft) is 8.12 in./yr (NOAA 1990) and increases with elevation across KAFB to a peak near 20 in. per year at approximately an 8000-ft elevation in the Manzano Mountains. The average monthly winter precipitation at the airport is less than 0.5 in. and summer precipitation is less than 1.5 in./mo. Summertime rainfall usually originates from small cells with substantial variation in intensity over short distances. Average annual snowfall for Albuquerque is 14.7 in. (NOAA 1990), the melted equivalent of approximately 2 in. of water (snow-water equivalent). Snow usually melts within 24 hr at lower elevations. Snow cover is common in the mountains from mid-November to early spring. Rough extrapolation of U.S. Department of Agriculture (USDA) Soil Conservation Service cooperative snow-course data from snow courses on surrounding mountains (all more than 60 mi distant) suggest that between 3 to 4 in. of snow-water equivalent should be present near peak snowpack accumulation (i.e., February 15 to March 1) at elevations of approximately 8000 ft in an average year.

Extreme precipitation values for points in Albuquerque include 0.5 in. in 5 min, 1.34 in. in 25 min, and 4.6 in. in 6 hr (Fischer et al. 1984, Metzker et al. 1993). Too few data are available to assign a recurrence interval to these intensities. Generalized precipitation intensity maps are available elsewhere (Miller et al. 1973).

In the 1950s and 1960s, SNL/NM installed and operated a meteorological monitoring network in support of experimental reactors in the northeast corner of TA-III (now TA-V). Ten years of data from this eight-station network were summarized and published in a technical report (Olsen et al. 1970). Data from this network currently exist solely in summarized hardcopy tables. A meteorological program designed to provide information about wind, temperature, humidity, precipitation, and the variation of these parameters in time and space began in 1994. Several towers were instrumented to measure wind direction, speed, temperature, humidity, barometric pressure, and rainfall (Plate I). Sensors on each tower are linked to a central facility capable of remote data collection and system checks, and data are being collected and archived by SNL/NM Organization 7575. Precipitation data for water-year 1995 (WY95) (i.e., October 1, 1994 through September 30, 1995) from the three towers with rain gages are given in Table 3.2.1-1.

Long-term records from National Weather Service gages at the Albuquerque International Airport suggest that annual rainfall has been substantially above average in most recent years (Figure 3.2.1-2). Conclusions drawn from analysis of hydrologic data over the past several years should consider the effects of above-average rainfall. Examples of hydrologic processes that may have been effected include surface runoff, soil-water movement in the vadose zone, and aquifer recharge through arroyos. Areas of aquifers that are responsive to short-term changes in recharge (particularly from arroyos) might also show some response to above-average rainfall. One location that may be in this category is the area near where Tijeras Arroyo enters KAFB.

Although recent annual precipitation totals have been above average, this does not necessarily imply that streamflow quantities were also above average. Local streamflow typically is a very small fraction of precipitation, and is largely dependent on the intensity and areal distribution of individual precipitation events. These factors may not be correlated with annual precipitation totals. The periods of record of local arroyo streamflow data are too short to draw conclusions.

3.2.2 Surface Runoff

The surface-water system within the SNL/KAFB area consists primarily of ephemeral (briefly flowing) drainages. These drainages experience channel losses that contribute to groundwater recharge and might influence the water-surface profile of the underlying aquifer. Of additional concern is the possible erosion and subsequent surface transport and redistribution of contaminants. There are several known springs, all within the tributaries to Arroyo del Coyote (Plate II). These include Coyote Springs (perennial), G-Spring (intermittent), Sol se Mete Spring (probably is perennial), and Burn Site Spring (intermittent).

The major surface drainages include Tijeras Arroyo, Arroyo del Coyote, and an unnamed drainage south of Arroyo del Coyote (SNL/NM 1993a). Except for two very short reaches of channel with intermittent flow, these drainages are all ephemeral within KAFB. Arroyo del Coyote joins Tijeras Arroyo approximately 2 mi upstream of where Tijeras Arroyo leaves KAFB. In contrast, the arroyo to the south of Arroyo del Coyote disappears in the vicinity of TA-III. The SWHC Project has funded the operation of four USGS gaging stations on lower Tijeras Arroyo and Arroyo del Coyote for several years (see Appendix A, Figure A-1). In 1994, four additional gages were installed by the SWHC Project on Arroyo del Coyote and Tijeras Arroyo (see Appendix A, Figure A-1). Several floodplain delineation efforts for SNL/KAFB were summarized previously (SNL/NM 1993a).

Floods and runoff occur most commonly during the summer thunderstorm season (July through September). The snow in the Manzano Mountains can produce local runoff in the mountains, although

Table 3.2.1-1. Precipitation Data Collected During WY95 at Towers Operated by Sandia National Laboratories/New Mexico Organization 7575

Date	SC1 Precipitation (in.)	A36 Precipitation (in.)	A21 Precipitation (in.)	Date	SC1 Precipitation (in.)	A36 Precipitation (in.)	A21 Precipitation (in.)
10/1	0.02	0.02	0.00	4/19	0.34	0.22	0.21
10/4	0.00	0.00	0.05	4/21	0.03	0.00	0.01
10/7	0.02	0.00	0.01	4/22	0.04	0.02	0.02
10/11	0.00	0.01	0.00	4/28	0.95	0.00	0.00
10/14	1.12	0.57	0.47	5/1	0.06	0.04	0.00
10/15	0.22	0.25	0.20	5/5	0.00	0.01	0.03
10/16	0.50	0.46	0.41	5/16	0.00	0.02	0.01
10/17	0.02	0.02	0.02	5/17	0.01	0.00	0.00
10/24	0.01	0.00	0.00	5/28	0.02	0.02	0.01
10/25	0.00	0.00	0.03	5/29	0.17	0.07	0.01
10/26	0.30	0.40	0.31	6/16	0.00	0.14	0.00
11/3	0.05	NA	0.02	6/26	0.12	0.00	0.17
11/4	0.01	0.00	0.00	6/29	0.01	0.02	0.06
11/8	0.02	0.04	0.04	6/30	0.00	0.00	0.01
11/11	0.76	0.74	0.71	7/4	0.01	0.01	0.00
11/12	0.76	0.71	0.72	7/7	0.00	0.00	0.14
12/5	0.46	0.42	0.39	7/15	0.01	0.00	NA
12/6	0.32	0.29	0.24	7/16	0.00	0.01	NA
12/30	0.02	0.01	0.00	7/18	0.36	0.93	NA
12/31	0.17	0.10	0.14	7/20	0.00	0.00	0.01
1/5	0.39	0.39	0.38	8/1	0.02	0.00	0.00
1/10	0.00	0.00	0.01	8/6	0.01	0.00	0.00
1/11	0.03	0.02	0.03	8/7	0.10	0.00	0.00
1/12	0.01	0.01	0.00	8/10	0.00	0.00	0.10
1/16	0.00	0.00	0.24	8/11	0.67	0.06	0.03
1/17	0.20	0.00	0.00	8/14	0.01	0.02	0.00
1/18	0.00	0.22	0.00	8/16	0.04	0.19	0.42
1/26	0.08	0.06	0.06	8/18	0.00	NA	0.12
1/27	0.01	0.00	0.00	8/20	0.17	0.00	0.00
1/29	0.02	0.04	0.02	8/21	0.06	0.00	0.00
2/15	0.18	0.10	0.06	8/22	0.04	NA	0.02
2/25	0.43	0.45	0.59	8/23	0.59	0.56	0.57
2/26	0.01	0.00	0.00	8/26	0.55	0.00	0.00
2/27	0.00	0.00	0.01	8/27	0.71	0.35	0.33
2/28	0.07	0.04	0.07	8/29	0.00	0.01	0.00
3/1	0.11	0.09	0.04	8/30	0.01	0.00	0.00
3/2	0.08	0.07	0.07	9/7	0.09	0.16	0.72
3/3	0.01	0.00	0.00	9/8	0.15	0.20	0.32
3/5	0.01	0.00	0.00	9/13	0.01	0.00	0.00
3/6	0.04	0.05	0.01	9/15	0.05	0.04	0.04
3/10	0.03	0.00	0.01	9/18	0.24	0.19	0.04
4/2	0.07	0.05	0.03	9/22	0.02	0.01	0.02
4/7	0.06	0.00	0.00	9/23	0.04	0.05	0.01
4/10	0.28	0.15	0.20	9/28	0.55	0.68	0.57
4/11	0.00	0.01	0.00	9/29	0.35	0.42	0.00
4/18	0.04	0.01	0.00	**Total**	13.55	10.25	9.59

Note: NA = Not available.

this rarely reaches the lower portions of the arroyos or the Rio Grande. Although none have occurred in Albuquerque recently, large frontal storms in the fall or winter have resulted in localized flooding in other nearby areas.

The small size of convective thunderstorms also makes modeling rainfall/runoff relationships difficult. Not only are a large number of recording rain gages needed, but a large number of streamflow gages would also be necessary; e.g., the runoff measured in Arroyo del Coyote near Coyote Springs may be generated on less than 1 mi^2 of the watershed, while no flow occurs on the other 20 mi^2. In this case, accurate modeling of the runoff would require a stream gage and a rain gage on the 1-mi^2 portion of the watershed that was active. Even with that, it is probable that rainfall from one storm may only impact half of the watershed. If two storms of identical areal distributions of rainfall amount and timing struck the same watershed, runoff from the two events may differ because initial soil-water conditions are different, or because the water from one event is colder (and therefore more viscous) than from the other. Snowmelt runoff would also have to be addressed. Understandably, observations of many runoff events would be needed before relationships between rainfall, snowmelt, and runoff could be established; this could take many years, and ER work at SNL/NM will probably be completed before such a model could be developed. Given a perfectly working model of rainfall/snowmelt and runoff relationships, to predict a large flood event with this model, the rainfall and snowmelt quantity and timing of the event causing the flood would still need to estimated; few local data are available to make this estimate. Note that even a perfect estimate of the magnitude of a "100-yr flood" (i.e., a flood that has a 1% chance of occurring in any given year) would not determine whether a flood of that size or larger will next occur tomorrow, 50 years from today, or 200 years from today. Simple probability computations show that there is a 37% chance that a flood equal to or larger than a "100-yr flood" will not occur within 100 years. Although SWHC Project staff will not be able to estimate peak streamflows from rainfall and snowmelt data, other techniques are available to estimate peak flood flows. While far from perfect, these techniques are probably adequate for any purpose required by the SNL/NM ER Project.

A regression technique published by the USGS (Waltemeyer 1986) may be used to predict floods with various recurrence intervals in this area. (As was just shown, the recurrence interval is a misnomer, but is equal to 1/probability of a given flood.) For example, the equation for the 100-yr flood in this region is:

$$Q_{.01} = 8.96 \times 10^5 \, A^{0.38} \, (Ec / 1000)^{-4.09} \, (I24,10)^{1.4}$$

where:

$Q_{.01}$ = Discharge in cubic feet per second (ft^3/sec) for the 100-yr flood (i.e., a flood that has a probability of 0.01 in any given year),

A = Watershed drainage area (square miles),

Ec = Average of channel elevations (feet) at points 10% and 85% of total channel length upstream of the point of interest, and

(I24,10) = 10-yr, 24-hr rainfall intensity (i.e., the amount of rain that falls in 24 hr during a large storm that occurs once in 10 yr on the average).

For a USGS gaging station on Tijeras Arroyo, the drainage area was given as 133 mi^2, the average of channel elevations as 5930 ft, and the 10-yr, 24-hr rainfall as 1.78 in. (Waltemeyer 1986). With these data, the above equation predicts a 100-yr flood of 8875 ft^3/sec for this station, with a standard error of estimate of +66% to -40%. This indicates that there is approximately a two-thirds chance that the true 100-yr flood lies between values 66% larger and 40% smaller than the predicted value, and a one-third chance that the true 100-yr flood lies outside this range. In addition, Waltemeyer (1986) cautions that "essentially no data exist in the Sandia Mountains"; most of the data used to develop these equations came from near Santa Fe. At present this technique is probably the best available for SNL/NM in spite of its limitations. Based on local observations, we suspect this technique overestimates local runoff, at least in moderate-sized basins. For example, Madera Canyon and the Burn Site/Sol se Mete drainages in upper Arroyo del Coyote both have two 4-ft-diameter culverts near their outlets. Each of these culverts can handle flows of approximately 100 ft^3/sec with a headwater elevation of 5 ft (SNL/NM 1995a, Appendix C, page C-12). Therefore, at either site, flows much in excess of 200 ft^3/sec would cross the road (No Sweat Boulevard), which would cause substantial erosion or perhaps loss of the culverts and roadway. The apparent age of these installations, ditch slopes, and associated vegetation do not suggest any such flows have occurred within the preceding decade. One of the pipes has a hole in its top, presumably caused by a backhoe removing debris from the culvert entrance, which suggests the culverts were able to handle most of the streamflow from a large event even when partially plugged.

In contrast, the USGS technique (Waltemeyer 1986) produces flow estimates for both watersheds that are approximately equal to the capacity of the paired culverts for a 2-yr event, and more than 300% of this capacity for 10-yr events. These observations are not robust enough to justify reducing flood-flow predictions but (by themselves) suggest that decisions based on flood predictions using existing (USGS) techniques are conservative.

In the fall of 1994, a large log (apparently cottonwood) was rediscovered lodged high on a rock above the stream channel of Arroyo del Coyote, about a mile or two downstream of Coyote Springs. This log was first reported in the 1990 groundwater monitoring report (SNL/NM 1991). Initial reconnaissance suggested that this log was deposited by flooding and probably came from the Coyote Springs area. The location of the log appears to be too dry to support cottonwood and no living examples are nearby. Because the wood has not rotted away, it was probably deposited during historical times, perhaps within the preceding 50 to 100 years. (It is supported by rock, and hence will not rot as fast as it would in contact with the ground.) The log's presence indicates that no significantly larger event has occurred since it was deposited. A larger event would have washed it away. Based on the log's location above the channel bottom and channel characteristics, a rough (and probably high) estimate of the flood flow that deposited it is 6300 ft^3/sec (Appendix A). This is approximately 175% of the 100-yr-flood flow calculated for this site (3600 ft^3/sec) using the USGS technique described above with the rainfall intensity used for the Tijeras Arroyo computation. We do not know exactly when this flood occurred; however, knowing when it occurred would not determine the recurrence interval of the flow with any degree of accuracy. The information gained by the cursory examination given to the event that deposited this log tends to support the acceptability of the USGS regression technique described above for flood-flow estimation. Whereas this event may have been somewhat larger than we would have expected from a flood in the preceding 100 years, observations based on the longevity of paired culvert installations suggested floods are smaller than we would expect. The SWHC Project has no current plans to gather additional streamflow data for flood peak estimation or for any other purpose.

Based on very limited data and observations during WY93 through WY95, rainfall events large enough to produce runoff do not typically produce more runoff at higher elevations around KAFB. To some degree, this difference in runoff production can be linked to the fraction of impermeable surfaces present on some watersheds; portions of the airport/air base/SNL/NM complex often produce more surface runoff in lower Tijeras Arroyo than do the approximate 80 mi^2 of the Tijeras Arroyo watershed upstream of those areas. This is often evident in data from upper and lower USGS gages on Tijeras Arroyo (Appendix A, Table A-1 and Figure A-1). However, the flows measured in 1994 at Gage 3 above Coyote Springs were often disproportionately larger than those measured further upstream at Gage 1 and Gage 2 (Appendix A, Table A-2 and Figure A-1), although very little development exists between those areas. This seems to suggest that moderately large storms are often more intense farther away from the mountains, which, although counterintuitive, is possible. This could also be a result of higher infiltration rates near the mountains. Data are too sparse to draw definite conclusions. Flows from the drainage just north of the Burn Site were never sufficient to collect a water sample for analysis, although several samples were obtained below the Burn Site. This may be attributed to development at the Burn Site. Lower peak flows at higher elevations are also forecast by the USGS flood-flow regression technique, which is caused by the negative exponent on the average channel elevation term. In this case, the difference is apparently attributed to floods caused by snowmelt at high elevations and by rainfall at lower elevations.

Data for WY95 from the four USGS gages were unavailable at the time this report was generated. Water-year 1994 data from these gages are provided in Appendix A. Four non-USGS gages installed during WY94 measure runoff from a total watershed area of approximately 100 mi^2, the majority of which is from Tijeras Arroyo outside the KAFB boundaries. Approximately 14.7 mi^2 of the total watershed area is measured twice (because the new gage above Coyote Springs, Gage 3, includes the watershed areas of Gages 1 and 2). The total runoff measured at all four non-USGS gages during WY95 (including those flows passing more than one gage and thus measured twice), was approximately 13.65 million cubic feet (ft^3) (313 acre-feet). To put this quantity in perspective, it is equal to an annual water supply for approximately 1,120 people at a use rate of 250 gallons per person per day or about 0.06 area-inches for the total watershed area. It is approximately 104% of flows passing the lower USGS gage on Tijeras Arroyo during WY94 (the prior water year). Runoff passing this USGS gage includes that generated on the majority of the KAFB watershed area, in addition to substantial off-base areas.

3.2.2.1 Arroyo-groundwater interactions

Technically, recharge to the aquifer occurs through the vadose zone, and therefore should be described in Section 3.3 of this report. However, the vadose zone beneath arroyos was assigned to the surface hydrology subtask for studies by the SWHC Project. For this reason, it is discussed herein.

Arroyo recharge is significant in that it may affect groundwater flow direction and velocity and (if the water is contaminated or flows over contaminated areas) may serve as a pathway for groundwater contamination. On-site tests have shown infiltration rates of pure water (i.e., sediment-free water) into coarse-textured arroyo channels average 15 to 30 ft/day (Appendix A, Table A-4); however, few hard data are available on actual recharge rates with natural flows of sediment-laden water over local arroyos.

In 1994, several neutron access tubes were installed to depths from 10 ft to approximately 80 ft in and near Tijeras Arroyo by the Kirtland Landfill (Appendix A, Figure A.1). Water contents in the soils around these tubes were measured 15 to 65 times each between mid-July of 1994 and the end of September 1995; frequency of measurement was proportional to the amount of change observed at each tube, with in-channel tubes receiving more measurements than those outside the channel. Two of three deep tubes (i.e., more than 50 ft) installed in the main channel of Tijeras Arroyo penetrated a fine layer near the surface that limited infiltration. The third tube in the main channel did not penetrate a fine layer, and more infiltration occurred near this tube. Tubes outside the channel showed a small but positive response to the infiltration occurring in the channel over the course of the year. Separate estimates of total aquifer recharge from 15 runoff events in WY95 were made for the in-channel tubes. The recharge estimates were 4 ft for those tubes penetrating fine layers and approximately 11 ft for the tube that doesn't penetrate a fine layer (Appendix A, Section A.6).

The significance of arroyo-channel-surface characteristics and fine soil layers underlying coarse-textured arroyo bottom materials was recognized in last year's SWHC Project report (SNL/NM 1995a). As a result, an arroyo survey was completed to identify (1) the width of channel surfaces exposed to infiltration, (2) infiltration rates and particle size of surficial arroyo-bottom materials, (3) the depth to fine layers beneath the channel surface, and (4) infiltration rates through buried fine materials. (Appendix A, Section A.7, summarizes these data.) It is believed that arroyo recharge from a typical runoff event can be estimated from the channel width and depth-to-fine layer measurements (Appendix A, Section A.7). Coupled with the estimated number of runoff events, these estimates for Arroyo del Coyote below the Lovelace Road bridge and for the length of Tijeras Arroyo on SNL/KAFB are equal to 400,000 cubic feet per year (ft^3/yr) and 2.2 million ft^3/yr, respectively, for an annual average of three and nine runoff events on those respective arroyos. These numbers of runoff events may have been influenced by above-normal precipitation (Figure 3.2.1-2).

Recharge through the portions of the channel bottom of Tijeras Arroyo on SNL/KAFB is relatively small. Recharge to the aquifer from upstream portions of Tijeras Arroyo may be significantly larger than that occurring on SNL/KAFB itself. Tijeras Arroyo flows continuously for months at a time upstream of SNL/KAFB above the Four Hills Bridge (USGS 1990, 1991, 1992a). Records at this site cover an approximately continuous period of about 28 months, and are described as poor (USGS 1990). Low flows comprise a large portion of total discharge measured at this site. The gaging station was designed principally for measuring low flows; thus low flow data values are likely to be more accurate than larger flow values in these data. The average discharge measured was 0.19 ft^3/sec for 850 days of records, or approximately 5.9 million ft^3/yr. Only an approximate 2% of this flow evaporated, suggesting that most became aquifer recharge (Thomas 1995), and most flow infiltrated before reaching the northern boundary of SNL/KAFB. During 1995, SNL/NM personnel observed larger (estimated) flows at this site than any measured during the period of USGS records (78 ft^3/sec) and in one case noted that the observed flow did not reach SNL/KAFB. Because of these observations and the poor records for larger upstream flows, the annual recharge from Tijeras Arroyo upstream of SNL/KAFB has probably been more than 5.9 million ft^3 in recent years.

3.2.2.2 Surface-water quality

Until last year, few surface-water quality samples were available for the SNL/KAFB area. Most samples that were available were representative of flows from parking lots and heavily developed areas. Efforts to obtain a more distributed set of surface-water quality samples from rainfall runoff events began in May 1994. These efforts were designed to improve knowledge of background concentrations of contaminants of concern, to help verify that areas thought to be free of contamination were in fact clean, and to help identify any contaminated areas that may have been overlooked. In addition, major ions were measured and subsamples were gathered for stable isotope analyses to help determine sources of groundwater recharge. Stable isotope analyses were performed only on 1994 samples.

Because surface runoff and areas where it is generated are thoroughly exposed to the atmosphere, water quality analysis performed by the SWHC Project focused on constituents that were nonvolatile. Any volatile organic chemicals that may have been present on the soil surface at some time were assumed to have evaporated and therefore would not be found in runoff. Constituents evaluated in 1995 included metals, radionuclides, and major anions (Appendix A, Table A-3).

No samples of surface water show indications of more than trace levels of constituents of concern.

3.2.2.3 Role of the surface runoff in contaminant transport

Surface runoff can be a significant factor in contaminant transport. First, it can erode surface materials and uncover and suspend previously buried contaminants. Second, once suspended, contaminants in surface runoff may be transported hundreds of feet within minutes, whereas transport in subsurface flows may require years to cover the same distance. Interaction with sediments results in little retardation of contaminants when the sediments are also moving with the water flow. Third, contaminated surface runoff may infiltrate the channel bottom and recharge the underlying aquifer far from the original contamination source. The net result of such hybrid surface/subsurface transport could be contaminated groundwater existing far from known sources of contamination, and far in advance of groundwater plumes emanating from the source.

Locally, SNL/NM may be considered fortunate considering the risks posed by contaminant transport in surface runoff. Notably, SNL/NM staff are aware of no major sources of contamination in areas where severe surface erosion is likely, and no clear evidence of contamination has been found in local surface-runoff waters.

3.2.3 Vadose Zone Hydrology

The vadose (or unsaturated) zone is the region located between the land surface and the groundwater system (the saturated zone) (Figure 3.2-1). The water table, defined as the surface on which the fluid pressure in the pores is exactly atmospheric, is commonly thought to be the boundary between the vadose zone and saturated zone (Freeze and Cherry 1979). The vadose zone provides the link between surface-water hydrology, which deals with surficial processes such as precipitation, snow melt, runoff, infiltration, overland flow and evapotranspiration, and groundwater hydrology, which is concerned with the flow and transport processes in aquifer systems (Gee and Hillel 1988).

The vadose zone is an important part of the hydrologic system in the SNL/KAFB area. In this semiarid climate, the vadose zone thickness is generally quite large; consequently, most contaminants released near the ground surface must travel a long distance before reaching the groundwater system. The majority of the ER sites are located at or near the land surface. The vadose zone east of the Tijeras/Hubbell Springs/Sandia fault complex ranges from approximately 50 ft thick in arroyos and valleys to several hundred feet thick near the faults. On the west side of the faults, the unsaturated zone is up to 500 ft thick. In the eastern valleys and arroyos, the vadose zone consists primarily of alluvial fill. In the eastern hills, however, fractured Precambrian, Pennsylvanian, and Permian bedrock materials are exposed at the ground surface. Section 3.1 and Attachment 1 provide more detail about the geology east of the fault complex.

Contaminant concentrations that reach the water table are a concern with respect to the Safe Drinking Water Act Maximum Contaminant Level (MCL), New Mexico Water Quality Control Commission (WQCC) groundwater standards, or site-specific derived action levels. Dispersive spreading in the vadose zone could dilute contaminant concentrations to the point that, when and if contaminants reach the water table, concentrations might be less than these standards. The regional areal recharge rate, which controls the upper boundary condition of the saturated zone, is also affected by vadose zone characteristics.

Where the water table is deep and the materials above it are very heterogeneous, flow and contaminant transport through the vadose zone can be very difficult to define (Gee and Hillel 1988). Some of the difficulties arise from technological limitations in measuring vadose zone properties. The physical measurements currently in use to determine flow- and transport-related properties of unsaturated porous media and their limitations are discussed by Dane and Molz (1991) and Wilson et al. (1994). Another problem is the incomplete understanding of vadose zone flow and transport processes, especially in areas with thick vadose zones. The influence of hydraulic property variability on unsaturated flow and transport, multiphase flow and transport, preferential flow and transport caused by macropore flow (e.g., large pores from cracks and root channels) and unstable flow (i.e., fingering), advective and diffusive flow of soil gas, and prediction of groundwater recharge in arid and semiarid climates are areas of current vadose zone research described by Gee et al. (1991) at another location that might provide methods for solving vadose zone problems in the SNL/KAFB area.

3.2.3.1 Sandia National Laboratories/Kirtland Air Force Base vadose zone setting

Important flow and transport processes in the vadose zone are highly interconnected with, and dependent on, many other facets of the hydrogeologic picture, such as climate, geomorphology, vegetation, geology, and the location of the saturated zone. In general, in the SNL/KAFB area, water enters the vadose hydrologic system as infiltrating rainfall and channel losses from flow in arroyos, and leaves the system as evapotranspiration to the atmosphere and recharge into the underlying aquifer. The following discussion briefly describes the interrelated hydrogeologic features important to the vadose zone in terms of their effects on our current conceptual model for flow and transport through the vadose zone in the SNL/KAFB area.

The SNL/KAFB area has a semiarid climate characterized by low precipitation, wide temperature extremes, frequent drying winds, some heavy rain showers (usually of short duration, often with erosive effects), and an erratic seasonal distribution of precipitation (Section 3.2.1). The average precipitation typically increases with elevation; thus, the distribution of precipitation varies in an increasing fashion from the western to the eastern portion of the area. This climate implies low recharge rates to the groundwater system from areal infiltration resulting from the low precipitation and high evapotranspiration conditions. Whether any areal infiltration (and consequent downward transport of contaminants to the water table) occurs through the geologic media between major arroyos is presently unknown. Recharge studies conducted on open rangeland at the Sevilleta National Wildlife Refuge south of Albuquerque indicate modern, deep, drainage rates ranging from millimeters to a couple of centimeters per year (Stephens and Knowlton 1986, McCord and Stephens 1987, Phillips et al. 1988), and recent observations at the Walnut Gulch Experimental Watershed in southeast Arizona showed significant moisture pulses moving below the presumed root zone (USDA 1992). By contrast, recent environmental isotope studies in the nearby Santa Fe basin suggest "negligible" recharge (USGS 1992a). Appendix B in this report describes a recharge study undertaken for SNL/KAFB. However, even a small interchannel areal recharge, integrated over a large area, can contribute a significant volume of water to the site-wide water balance.

There are no continuously running streams in the SNL/KAFB area, although there is a system of arroyos that flow ephemerally, primarily during or after large thunderstorm events. In this vicinity, Tijeras Arroyo and Arroyo del Coyote are probably the largest localized recharge sources (USGS 1992a). The magnitude of arroyo flow loss as a result of evapotranspiration and infiltration into the vadose zone (causing possible recharge to the groundwater system) is unknown, but was under study (see Section 3.2.2.1 and Appendix A).

The major vegetation types in the SNL/KAFB area tend to vary with elevation, slope, and aspect. Generally, woodlands are found in the eastern portion of the area in the Manzanita Mountains and canyons, whereas grasslands cover the western portion of the area on the lower elevations. The land-surface percent slope in the SNL/KAFB area varies from less than 1% to greater than 46%. Most mountain ridges trend to the northeast-southwest; therefore, many of the steep slopes face either southeast or northwest. Vegetation characteristics and slope affect the surface runoff and potential infiltration rates. Steep slopes facing the southeast receive more sunshine for longer periods of time than those facing northwest, causing different potential evapotranspiration rates to occur on southeast- versus northwest-facing slopes.

Soils in the SNL/KAFB area consist primarily of well-drained loamy soils, with gravely and stony soils along the arroyos and on the mountains. The USDA Soil Conservation Service (Hacker 1977) has designated the permeabilities and available water capacities of the soils in the area based on the mapped soil textures. Permeabilities are mainly moderately slow to moderately rapid (0.2 to 6 in./hr) in the area, whereas the canyon bottoms and the Tijeras Arroyo floodplains exhibit rapid (6 to 20 in./hr) permeabilities. Available water capacity is inversely correlated with the permeabilities (i.e., high water capacity corresponds with low permeability, as in a clayey soil). Infiltration is more likely to occur in areas with high permeabilities, because areas with low permeabilities have greater surface runoff potential. Where no permeability data exist, regions are classified as rock outcrop with very low matrix permeabilities. If the rock outcrops are fractured, the fracture-flow permeabilities might be very high, creating zones at high elevations (that correspond with the highest annual precipitation) where significant infiltration into the system could occur. The actual surface and subsurface conditions of the rock outcrop areas are not well known. SNL/NM feasibility study results on outcrop fracture characterization are reported in SNL/NM (1995a). Observations from this study indicated that a significant percentage of bedrock fractures are open. This suggests that bedrock areas may be effective recharge regions. Furthermore, there is significant variability in fracture orientations.

Underlying the generally poorly developed soils, the vadose zone generally consists of unconsolidated alluvial deposits. These deposits consist of unconsolidated and semiconsolidated sands, gravels, silts, and clays of the Santa Fe Group (see Section 3.1.2.5) and younger surficial deposits (Section 3.1.2.6). On the west side of the SNL/KAFB area, these alluvial deposits are composed of highly heterogeneous alluvial fan, fluvial, and aeolian deposits. Farther west of SNL/NM facilities, the distal alluvial-fan materials interfinger with generally finer Rio Grande sediments. In the eastern portion of the SNL/KAFB area, there are areas where the vadose zone is composed of bedrock materials (e.g., Precambrian, Pennsylvanian, or Permian formations) of relatively low permeability, but these bedrock materials may be highly fractured locally. Surficial deposits in the eastern SNL/KAFB area that make up the vadose zone also are heterogeneous alluvial-fan and fluvial-terrace deposits.

Because of the large size and hydrogeologic diversity of the SNL/KAFB area, a systematic approach was needed to assist in selecting vadose zone test sites. A study was conducted to identify prototypical vadose zone hydrogeologic settings in the SNL/KAFB area, so that vadose zone characterization tests could be conducted within each setting (Parsons et al. 1993). The characterization results from a particular setting can then be applied to all ER sites within that setting. Using this approach, the site characterization process is less subjective and less costly because it is no longer necessary to perform complex vadose zone tests at each individual ER site.

A GIS was used to compile selected data layers that may influence infiltration and vadose zone transport characteristics. The data layers were qualitatively compared and contrasted using ArcView™, a GIS visualization and query software package. Vegetation, slope, soil permeability, and soil available water capacity (AWC) were thought to have the most effect on infiltration characteristics. Therefore, these data layers were chosen for this study. The vadose zone hydrogeologic settings were designated based on a new data layer formed by combining simplified versions of the original data layers. Nine vadose zone hydrogeologic settings were identified (Figure 3.2.2-1) and included:

- Setting 1: Arroyo and canyon vegetation, low to high slope.
- Setting 2: Rock outcrop, medium to high slope.
- Setting 3: Grassland, low to medium slope, high permeability, medium AWC.
- Setting 4: Grassland, low to medium slope, high permeability, low AWC.
- Setting 5: Grassland, low to medium slope, medium permeability, low to high AWC.
- Setting 6: Open- to closed-canopy woodlands, low to medium slope, high permeability, low AWC.
- Setting 7: Open- to closed-canopy woodlands, low to medium slope, medium permeability, low to high AWC.
- Setting 8: Closed-canopy woodlands with low to medium slope, open- to closed-canopy woodlands with high slope, low permeability, high AWC.
- Setting 9: Open- to closed-canopy woodlands, high slope, medium permeability, low to medium AWC.

Parsons et al. (1993) provide a full discussion of the study that identified the nine vadose zone hydrogeologic settings.

Although nine different vadose zone settings were identified, vadose zone field tests were not performed in each setting. For example, the arroyo and canyon setting (Setting 1) was characterized by the SWHC Project surface-water group. Most of the planned tests could not feasibly be performed in the rock outcrop setting (Setting 2) or the woodlands setting with high slope (Setting 9) because of the infiltration characteristics of those areas. No field tests were planned for Setting 8 because no ER sites are located within that setting. Thus five settings remained to be characterized: Settings 3, 4, 5, 6, and 7. For Setting 3, many samples were obtained below the root zone for the Tijeras Arroyo infiltration test (described in Appendix B.1 and Attachment 3). For Settings 4 and 5, dozens of samples below the root zone were obtained as part of detailed recharge studies undertaken for the Mixed Waste Landfill (MWL), the Chemical Waste Landfill (CWL), and the South Fence Road project. For Settings 6 and 7, samples used were taken from the bottom of some of the geology soil pits for chloride analysis. The results of these studies indicate that the recharge rates for these settings are quite small. The recharge estimates range from 1 to 6 millimeters per year (mm/yr). This range is well below the 2-cm/yr threshold rate identified in the risk-based transport analysis in the 1993 SWHC Annual Report (SNL/NM 1994a). This suggests that, for sites where natural recharge is the primary mode of aqueous phase transport, solutes have traveled only a very shallow distance in the soil profile, and that any needed remediation could be accomplished via excavation of shallow soils. See Appendix B.2 for more detail about the recharge analyses.

Previous studies

Vadose zone investigations conducted prior to 1995 are summarized in the 1992 Site-Wide Hydrogeologic Characterization Project Annual Report (SNL/NM 1993a), the 1993 Site-Wide Hydrogeologic Characterization Project Annual Report (SNL/NM 1994a), and the 1994 Site-Wide Hydrogeologic Characterization Project Annual Report (SNL/NM 1995a). Table 3.2.3-1 presents a summary of important saturated and unsaturated flow parameters and processes measured within the SNL/KAFB area.

The numbers in the top eighteen rows in Table 3.2.3-1 indicate the number of samples analyzed for the particular parameter in the referenced study. For example, the number 30 in the cell at the intersection of the row labeled Stephens and Associates (1990a and 1990b) and the column labeled K_{sat} indicates that there are thirty saturated hydraulic conductivity results given in those reports. Similarly, the number 20 in the cell at the intersection of the row labeled McTigue and Stein (1990) and the column labeled K_{unsat} indicates there are twenty unsaturated hydraulic conductivity results given in that report.

The rows labeled Minimum, Mean, and Maximum at the bottom of the table refer to, respectively, the low, mean, and high values of the results obtained from the studies. For example, the results in the bulk density column indicate that, for the 14 samples available, the minimum bulk density result was 1.60 grams per cubic centimeter (g/cm^3), the mean bulk density was 1.81 g/cm^3, and the maximum bulk density result was 2.12 g/cm^3.

Calendar year 1995 studies

Several vadose-zone hydrology studies relevant to the SNL/NM ER Project were undertaken in calendar year 1995. First, work continued on the instantaneous profile (IP) test implemented in December 1993 at the MWL (SNL/NM 1993b). Various unsaturated hydraulic properties were determined for use in modeling unsaturated flow and contaminant transport from the MWL. In addition, the natural recharge rate was estimated to be between 10^{-7} to 10^{-8} centimeters per second (cm/sec) in soils with approximately 10% volumetric moisture content. The test results are summarized in an SNL/NM report (SNL/NM 1995b).

Second, members of the SWHC Project and the SNL/NM Geohydrology Department (Organization 6115) conducted the Tijeras Arroyo infiltration test, the preliminary results of which are summarized in Attachment 3 (also see Appendix B.1 for an introduction). The main objectives of this test were to (1) obtain information (infiltration rates, rates of wetting front advance, and moisture content and pressure data) to elucidate flow processes operating in heterogeneous, unsaturated, geologic deposits at SNL/NM ER sites, (2) provide in situ hydraulic property data for comparison to data obtained from laboratory analyses of site samples, and (3) use the test results to develop guidelines for ER site project leaders for characterization and assessment of vadose zone problems.

Third, three field studies were undertaken to characterize ambient recharge across the site. These studies utilized environmental tracers to quantify recharge, and they included investigations into the

Table 3.2.3-1. Numbers of Saturated and Unsaturated Hydraulic Property Tests and Range of Values Encountered in Those Tests

Investigation	Location	Grain Size	q_i[a]	r_b[b]	K_{sat}[c]	q-Y[d]	K_{unsat}[e]	Total Organic Carbon (mg/kg)	P[f]	vGP[g]
Persaud and Wierenga (1982)	CWL/MWL	44	37	14				3		
IT (1985)	CWL							24		
McTigue and Stein (1990)	CWL				20	20	20			20
Stephens and Associates (1990a and 1990b)	CWL/MW-4	30	30		30	30	30		30	30
IT (1992)	Sanitary Sewer Line	64			61 (K_{sat90}) 45 (K_{sat50})					
SNL/NM (1995c)	CWL MW-6	83	57	38	36				85	
SNL/NM (this report)	CWL Recharge	298	260	2					2	
SNL/NM (1995d)	SWHC I-25	301							123	
SNL/NM (1995e)	SWHC CTF-BH	61							36	
SNL/NM (1995e)	SWHC Kest	9							6	
SNL/NM (1995e)	SWHC Arroyo	23	16	3	16				3	
SNL/NM (1995e)	SWHC Trench	316		133					166	
SNL/NM (1995f)	TA-I	56	13	34	30				34	
SNL/NM (1995b)	MWL IP Site	6			18	13	66			
SNL/NM (1995d)	TA-II-NW1		58	27						
SNL/NM (in press)	MWL-RFI-II		315							
SNL/NM (1995e)	SWHC NA4		13		13					
SNL/NM (this report)	TJA[h]		69			34				
Total		1291	859	251	224	97	116	27	485	50
Minimum		i	0.20	1.00	5E-9	i	i	160	16.93	i
Mean		i	5.50	1.66	7E-3	i	i	539	34.39	i
Maximum		i	34.27	2.20	3E-1	i	i	2200	64.00	i

[a]q_i = Initial (gravimetric) moisture content (%).
[b]r_b = Bulk density (g/cm^3).
[c]K_{sat} = Saturated hydraulic conductivity (cm/sec).
[d]q-Y = Saturation versus pressure relationship.
[e]K_{unsat} = Unsaturated hydraulic conductivity (cm/sec).
[f]P = Porosity (%).
[g]vGP = van Genuchten parameters (q_{sat}, q_{resid}, a, and N). (Parameters used in defining the pressure vs. moisture content relationship of a soil.)
[h]TJA = Tijeras Arroyo Infiltration Experiment (see Attachment 3).
[i] = Unable to list meaningful range of values.

effects of heterogeneity and reverse osmosis on tracer transport. (Appendix B.2 summarizes these vadose zone investigations.) The first field study used chloride analyses of soil-water extracts from samples obtained from the geologic trenches to estimate natural recharge rates in representative vadose-zone hydrogeologic settings across the study area. The other two studies assessed the reliability of the tracer approaches at the SNL/NM site; the first focused on the impact of spatially variable water movement on tracer recharge estimates, and the second considered the potential impact of fine-grained layers on recharge estimates. The results of these studies indicate that the recharge rates for these hydrogeologic settings are quite small; recharge estimates range from 1 to 6 mm/yr.

3.2.3.2 Role of the vadose zone in contaminant transport

As stated in Section 3.2.3, the vadose zone is an important part of the hydrologic system in the SNL/KAFB area, and it plays a major role in contaminant transport. Because the vadose zone is generally quite thick here, most contaminants released near the ground surface would have to travel to great depths before entering the groundwater system. Whereas some contaminants may sorb strongly to the near-surface sediments in the vadose zone and may be so retarded that they never reach the water table, others may move down through the vadose zone fairly rapidly in the vapor phase. Still others dissolved in the aqueous phase may move at an intermediate pace along with the soil water.

Because the sediment materials at SNL/KAFB are heterogeneous, flow and contaminant transport through the vadose zone are difficult to define (Gee and Hillel 1988). Furthermore, vadose zone flow and transport processes are only incompletely understood. Dispersive effects in the vadose zone may dilute original contaminant concentrations over time and distance. Other factors, such as groundwater recharge rates, the effects of unstable flow (i.e., fingering), preferential flow and transport due to macropore flow (e.g., large pores from cracks and root channels), multiphase flow, and advective and diffusive flow of soil gas influence contaminant transport through the vadose zone.

3.2.4 Groundwater Hydrology

This subsection provides a summary description of the SNL/KAFB installation-wide groundwater hydrology. This summary description is a synthesis of information from professional hydrogeologic reports, SNL/NM ER Project investigations, ongoing SWHC Project studies, and other environmental characterization programs being carried out on the KAFB facility. These independent programs include the KAFB IRP, the ITRI facility investigation, and the SNL/NM Groundwater Protection Program (see Section 2.4).

3.2.4.1 Regional groundwater setting

The SNL/KAFB area is located in the eastern portion of the Albuquerque basin (see Figure 3.1.1-1). The Albuquerque metropolitan area, including SNL/KAFB, relies on the groundwater in this basin as the principal source of its water supply. The basin is part of a series of large basins extending from southern Colorado to the border with Mexico at El Paso. These basins are associated with south-trending structural features of the Rio Grande rift system (Hawley and Haase 1992).

The Albuquerque basin, located in central New Mexico covers approximately 2100 m^2. The basin is approximately 70 mi long and ranges in width from 10 mi in the north to 40 mi near the center. The vertical thickness of the basin fill sediments exceeds 14,000 ft in some areas (Hawley and Haase 1992). The eastern boundary of the basin is a series of faults running parallel to the fronts of the Sandia, Manzanita, and Manzano Mountains. The western edge is defined by faults that extend south-southeast from near the Jemez caldera to the Ladron Mountains near Socorro (Thorn et al. 1993). The northern extent is defined by Hawley and Haase (1992) at the San Felipe fault belt near Algodones. To the south, the basin is bounded by the Joyita Uplift near Socorro.

The stratigraphy of the basin fill sediments is divided into the lower, middle, and upper Santa Fe Group. The major freshwater aquifer(s) in the basin are located within the upper Santa Fe Group and, to a limited extent, in the middle of the sequence. The deposition of the upper unit and its characteristic sedimentary structure are associated with the evolution of the basin from an internally drained, closed basin to one drained by the through-flowing Rio Grande. This significant alteration of the hydrology of the basin began approximately 5 Ma (Hawley and Haase 1992) and resulted in the aggradation of the upper Santa Fe sediment sequence.

The upper Santa Fe sediments attain a thickness of up to 1200 ft (Hawley and Haase 1992). The sedimentary framework for this unit is characterized by intertonguing piedmont-slope and fluvial valley-floor deposits. The alluvial and debris flow materials characteristic of piedmont slopes consist of poorly sorted, weakly stratified sand and conglomerate with a silt-clay matrix. The fluvial deposits include cross-stratified channel deposits characterized by thick zones of clean sand and well rounded gravel, and fine- to medium-grained overbank sediments. Major basin aggradation ceased about one million years ago and post-Santa Fe deposition is the result of a series of episodes of river incisions and partial backfilling. The most recent surficial sediments include fan, eolian, and floodplain deposits including some volcanics (Hawley and Haase 1992).

Over the last 10,000 to 15,000 yr, the excess inflow of sediments from tributaries of the Rio Grande has resulted in aggradation of the central valley. This valley fill is as much as 200 ft thick and functions as a shallow alluvial aquifer. In much of the inner valley, layers of clay up to 15 ft in thickness within the alluvium disconnect the alluvial aquifer from the underlying Santa Fe Group. North of Interstate 40, the clay layer is near the surface and the Rio Grande has downcut through the layer and re-established a hydraulic connection with the regional aquifer. South of the interstate, the clay layer occurs at greater depth, and the river remains isolated from the main aquifer (Thorn et al. 1993). This low permeability layer limits potential recharge from the river and other surface water sources.

Most of the City of Albuquerque's wells are completed in the upper Santa Fe Group with some extending into the middle unit. The processes and sediment sources that resulted in the deposition of the upper portion of the Santa Fe Group provide more suitable aquifer material and structure (interbedded sands and gravels) than do the lower units that are made up of basin-floor playa-lake deposits (silts and clays) (Thorn et al. 1993). The most productive wells are located east of the present course of the Rio Grande and west of the most eastern excursions of the ancestral river channel. The lithologic characteristics of these axial channel deposits and, to a lesser extent, the materials of the pediment slope and alluvial fans, provides the best aquifer material of the basin sediments. Conductivity values as high as 130 ft/day have been determined through well tests (i.e., in well Leyendecker 1) in this portion of the basin. In contrast, wells tested in the western portion of the basin may attain maximum values of conductivity no greater than 25 ft/day (Thorn et al. 1993).

The water table slopes at a low gradient diagonally down-valley from the foothills of the Sandia and Manzano Mountains on the east and from the Rio Puerco on the west. The low point of the water table is located in a groundwater trough that trends southward approximately 8 mi west of the course of the Rio Grande. The water table in the trough is reported to be 30 to 40 ft lower than the water table under the river (Thorn et al. 1993). Local cones of depression associated with the large amount of groundwater pumping at the city's well fields have altered the direction of groundwater flow in the areas of influence of these fields. Pumping in excess of recharge has led to significant declines of the regional water table. This lowering is not uniform and is most pronounced along the eastern edge of the basin where the cones of depression of the wells in this area are bounded by the Sandia fault (Figure 3.1.1-3). The area of the largest water-level decline is just to the north of KAFB, on the west side of the Sandia fault. In this area, the water level has declined approximately 140 ft since 1960 (Thorn et al. 1993).

3.2.4.2 Sandia National Laboratories/Kirtland Air Force Base groundwater setting

The fault system that forms the eastern boundary of the basin bisects the area occupied by SNL/KAFB. The north- to south-striking Sandia fault enters the base from the north; almost colinearly the Hubbell Springs fault extends from the south, and the Tijeras fault cuts the base diagonally from the northeast (see Figure 3.1.1-3). The topography is characterized by a series of coalescing alluvial fans of Holocene age that extend from the base of the mountains to the east to terraces along the river. East of the Hubbell Springs and Sandia faults, the fan deposits rest on eroded pediment slopes (Thorn et al. 1993). Paleozoic and Precambrian rocks outcrop at various locations east of the faults. The north- to south-trending fault complex divides the local groundwater system into three distinct hydrogeologic regions. The region west of the fault system is identified as Hydrogeologic Region 1 (HR-1). Hydrogeologic Region 2 (HR-2) is associated with the fault system, and Hydrogeologic Region 3 (HR-3) is located east of the fault system (SNL/NM 1994b). Figure 3.2.4-1 shows the locations of the three hydrogeologic regions. The boundaries between these regions serve only to identify approximate geographic areas. Section 4.2.2 includes a more detailed discussion of the hydrogeology in each of these regions.

Hydrogeologic Region 1

The uppermost aquifer underlying HR-1 is within the upper Santa Fe Group, and is an unconsolidated to partially indurated, porous-media aquifer. The upper Santa Fe Group sediments that provide the framework for this aquifer include a heterogeneous mix of coarse- to fine-grained sands, silts, and clays that exhibit a complex sedimentary framework, characterized by variability in bedding thickness, continuity, and connectivity. The complex sedimentary framework includes the intertonguing of ancestral Rio Grande fluvial facies with alluvial fan facies extending westward from the highlands to the east. The fluvial facies includes thick, well-sorted, cross-stratified sand and pebbly, gravel channel deposits, and fine- to medium-grained sand overbank deposits. This fluvial facies is characterized by well developed bedding, with channel deposits generally oriented north-south. The alluvial fan facies is characterized by poorly sorted, weakly stratified sand and conglomerate with an abundant silt and clay matrix. In this facies, the bedding is less continuous with channel deposits generally oriented east-west.

The upper Santa Fe Group aquifer underlying the SNL/KAFB area is part of the City of Albuquerque's municipal water supply. Since 1960, water levels in this aquifer are estimated to have declined approximately 100 ft at the northern KAFB boundary to approximately 50 ft at the southern KAFB boundary (Thorne et al. 1993). Documents addressing the hydrogeology in this region include publications by SNL/NM (1994a, 1995a), Kernodle et al. (1987, 1995), Thorn et al. (1993), Hawley and Haase (1992), Lozinsky (1988), Kernodle and Scott (1986), SAIC (1985), Kelley (1977), and Bjorklund and Maxwell (1961).

Hydrogeologic Region 2

HR-2 straddles the Sandia/Tijeras/Hubbell Springs fault complex. The subsurface geology of HR-2 includes Santa Fe Group sediments to the south, a poorly to moderately cemented Tertiary conglomerate near the center, and Paleozoic/Precambrian bedrock to the north. The saturated zone hydrology is characterized by a flow system complicated by the juxtaposition of different stratigraphic units across one or more faults. In addition, the faults themselves have a significant impact on groundwater flow. Appropriate documents related to the hydrogeologic framework in this region include publications by SNL/NM (1994a, 1995a), Haneberg (1995), USGS (1992b), Lozinsky (1988), Grant (1982), Riddle and Grant (1981), Kelley (1977), Kelley and Northrop (1975), and Titus (1963).

Hydrogeologic Region 3

HR-3 is located in the eastern portion of the area occupied by SNL/KAFB. The bedrock stratigraphy includes an unnamed lower Tertiary unit; Paleozoic Yeso, Abo, Sandia, and Madera formations; and Precambrian igneous and metamorphic rocks. This general stratigraphic framework is complicated by faulting. Overlying portions of the bedrock is a thin veneer of piedmont alluvial material. The saturated zone hydrology includes shallow, unconfined alluvial aquifers (especially in the foothill canyons) and confined bedrock aquifer systems. The bedrock aquifers include one or more confined porous-media aquifers in sandstones of the Paleozoic units (Yeso, Abo, and Sandia formations), and one or more confined fractured aquifers in the Paleozoic Madera limestone and Precambrian rocks. Appropriate documents related to the hydrogeologic framework for this region include publications by SNL/NM (1994a, 1995a), Calvin et al. (1982), Titus (1980), Kelley (1977), Myers and McKay (1970, 1976), Kelley and Northrup (1975), and Reiche (1949).

3.2.4.3 Groundwater characteristics

Groundwater characteristics within the SNL/KAFB area vary between and within the three hydrogeologic regions. These characteristics include aquifer type (i.e., unconfined/confined, porous media/fractured rock, and regional/perched), hydraulic properties (hydraulic conductivity, storativity, and porosity), horizontal groundwater-flow directions, vertical hydraulic gradients, trends in water level decline due to water supply pumping, and groundwater geochemistry. Many of these characteristics are directly related to the geologic media that provide the local framework for the regional aquifer. Plate III shows the geologic units at the water table (upper limit of saturation of the uppermost regional aquifer).

3.2.4.3.1 Aquifer types

The regional aquifer underlying HR-1 and the southern portion of HR-2 is a porous media aquifer in the upper unit of the Santa Fe Group. In HR-1, this upper unit includes two depositional facies: a fluvial facies deposited by the south-flowing ancestral Rio Grande and an alluvial fan facies deposited into the basin from the eastern mountains. These two facies intertongue along a north-south trend which bisects the SNL/NM TA-III/TA-V area. In the alluvial fan facies, field data from boreholes drilled in 1992 at the SNL/NM Liquid Waste Disposal System (LWDS) site and the SNL/NM MWL indicate that the uppermost part of the aquifer is semiconfined (SNL/NM 1993b). In these boreholes, the water level rose slightly above the depth where the saturated zone was first encountered.

Shallow groundwater above the regional aquifer has been identified in the vicinity of Tijeras Arroyo underlying a large area extending from the Tijeras Arroyo Golf Course northwest to the WYO-1 monitoring well location (Plate II). This shallow groundwater may be associated with a system of multiple perched aquifers in the alluvial fan facies which result from recharge from Tijeras Arroyo (SNL/NM 1995a, 1994a). Other potential contributing sources include local recharge from irrigation at the golf course, and possibly septic systems and other drainfields (see Section 4.2.2.1.3). Shallow saturation may exist at other areas where natural or induced recharge is concentrated.

The uppermost aquifer in HR-2 is found in three very different types of geologic media (see Section 4.2.2.2). In the southern portion of HR-2, the uppermost aquifer is a semiconfined, porous media aquifer in the alluvial fan facies of the upper Santa Fe Group. In the central portion of HR-2, near the intersection of the Tijeras and Sandia faults, the aquifer unit is a poorly to moderately well-cemented Tertiary conglomerate. At the solar tower west (STW) monitoring well location (Plate II), one borehole was drilled to a total depth of 500 ft and was still in the conglomerate (see Appendix C). During drilling at the STW location, several intervals of significant lost circulation were encountered in the conglomerate. These lost circulation intervals may be caused by uncemented zones within the conglomerate or fractures within cemented zones. Based on these observations, the aquifer in this area of HR-2 is probably confined, and may exhibit both porous media and fracture flow characteristics. The northern portion of HR-2 includes that area between the Sandia fault and the Tijeras fault. In this area, the uppermost aquifer may be in the thin alluvial cover or in the underlying granitic bedrock. Where a shallow alluvial aquifer is present, it will be an unconfined, porous media aquifer. Where the uppermost aquifer is in the granitic bedrock, it will be a confined, fractured aquifer.

In HR-3, the uppermost aquifer is found in shallow alluvium, occurring locally in the foothill canyons and on the gently sloping piedmont surface in the southern part of the region on the south, and in various bedrock units (see Plate III). Where the shallow alluvium is saturated, it will be an unconfined, porous media aquifer. Groundwater occurrence in the bedrock aquifer will include both confined, porous media aquifers in sandstone/siltstone units and confined, fractured rock aquifers in limestone and igneous/metamorphic rock.

3.2.4.3.2 Hydraulic properties

The hydraulic properties summarized in this section include hydraulic conductivity, storativity, and porosity for the Santa Fe Group units in HR-1 and HR-2, and shallow alluvium and bedrock units in HR-3. Plate III shows the location of monitoring wells where hydraulic conductivity has been estimated from aquifer pumping tests.

Santa Fe Group units in HR-1 and HR-2

The surface of the uppermost Santa Fe Group regional aquifer underlying the KAFB/SNL/NM area is found in the ancestral Rio Grande fluvial facies to the west and alluvial fan facies to the east (Plate III). Based on an assessment of the ratio of (sand + gravel)/(silt + clay) in various lithofacies of the Santa Fe Group, Hawley and Haase estimated that hydraulic conductivities in the Upper Santa Fe Group could range from less than 0.3 ft/day in alluvial fan facies to more than 30 ft/day in the fluvial facies (Hawley and Haase 1992). Given this large range in hydraulic conductivity values for these two different lithofacies of the Santa Fe Group, it is important that the existing data be correlated to the proper facies.

Ancestral Rio Grande fluvial facies — Hydraulic conductivity data for the ancestral Rio Grande facies are available from aquifer pumping tests performed on water supply wells. (These wells are generally screened over large intervals which include thick sections of the fluvial facies.) Slug tests and aquifer pumping tests in monitoring wells known to be completed in the fluvial facies also provide data. Table 3.2.4-1 summarizes hydraulic conductivity data obtained in wells completed in this facies.

Table 3.2.4-1. Hydraulic Conductivity for Ancestral Rio Grande Fluvial Facies of the Santa Fe Group

Data Source	Data Type	Hydraulic Conductivity (ft/day)
Data from Other Publications		
Hawley and Haase (1992)	Estimated for the fluvial facies	> 30.0
KAFB IRP Investigation (USGS 1993)	Slug test analysis (KAFB IRP monitoring wells in fluvial facies)	0.2 to 10.5
Water supply well analysis (GMI 1988a, 1988b)	Pumping test analysis (Yale and Burton well fields)	12.0 to 121.5
Data from SNL/ER Projects		
Site-Wide Hydrogeologic Characterization Project	1995 pumping test analysis at PL-2 and MRN-1 (Appendix D)	26.0 to 147.1
	1995 slug test analysis at PL-2 and MRN-1 (Appendix D)	0.26 to 2.6

Comparison of the slug test-data analysis results from the PL-2 and MRN-1 monitoring wells to the aquifer pumping test-data analysis results shows that slug tests in this facies may yield data that significantly underestimate hydraulic conductivity. This comparison suggests that the results of slug tests may not be representative of the true hydraulic conductivity for this facies. It is noted that the KAFB IRP monitoring wells were also drilled using drilling mud.

Porosity data for the ancestral Rio Grande fluvial facies is available from two SNL/ER sampling activities. Porosity values from 22 samples were derived empirically from grain-size distribution data, with approximate ranges of 0.26 to 0.45 (SNL/NM 1995d).

Alluvial fan facies — The uppermost water-bearing unit in the alluvial fan facies south of Tijeras Arroyo consists of up to 50 ft of silty clay. Below this fine-grained unit is an interval of approximately 85 ft which includes several coarser-grained layers, each approximately 10 to 15 ft thick (SNL/NM 1995g). Most monitoring wells are completed in the upper fine-grained unit which generally has a low hydraulic conductivity and acts semiconfined. At several locations in the TA-III/V area, there are monitoring wells completed in one or more of the underlying coarser-grained intervals. The hydraulic conductivity in these intervals is higher, while the hydraulic head is lower than the head in the overlying fine-grained unit. At the CWL, monitoring wells completed in a deeper, coarser-grained interval and separated by a horizontal distance of up to 300 ft responded together during an aquifer pumping test (MW-2B [lower], MW-5 [lower], and MW-6 [lower]) (locations shown on Plate III).

This indicates that the coarser-grained intervals are relatively continuous at the scale of the CWL and suggests that the sand intervals are hydraulically connected to the fluvial facies to the west and could be more responsive to water supply pumping in the City well fields to the north. If this hypothesis is correct, it could explain the lower hydraulic head in these sand intervals.

Hydraulic conductivity data for the alluvial fan facies are available from aquifer pumping tests performed on water supply wells located east of the eastern limit of the fluvial facies. (These wells are screened over large intervals which may include intervals of fluvial facies which intertongue with the predominant alluvial fan facies.) Slug tests and aquifer pumping tests in monitoring wells known to be completed in this facies also provide data. Table 3.2.4-2 summarizes hydraulic conductivity data obtained in wells completed in this facies.

A few aquifer tests have been accomplished in perched aquifer intervals in the alluvial fan facies in the vicinity of Tijeras Arroyo. Table 3.2.4-3 summarizes hydraulic conductivity data obtained in wells completed in perched aquifer intervals.

Porosity data for the alluvial fan facies are available from eight SNL/ER sampling activities. Porosity values from 431 samples ranged from 0.17 to 0.64 (SNL/NM 1995c,d,e,f,h). Some samples were measured directly, and others were derived empirically from grain-size distribution data. Three samples were collected and measured directly from locations along Tijeras Arroyo and Arroyo del Coyote. The porosity of these samples ranged from 0.35 to 0.48 (SNL/NM 1995e).

Calculated storage coefficients are available from aquifer pumping tests in the Ridgecrest well field, an aquifer pumping test at the SNM/NM CWL, and from the analysis of drawdown-recovery data at monitoring well TA2-NM1-595 resulting from pumping of KAFB-11 (Plate II). Table 3.2.4-4 summarizes these storativity values. Storativity of a confined aquifer ranges from 0.005 to 0.00005, while specific yield (the storage parameter for an unconfined aquifer) ranges from 0.01 to 0.30 (Freeze and Cherry 1979). This suggests that the low calculated storage coefficients indicate the Santa Fe Group aquifer should be considered a confined aquifer.

Bedrock and alluvial aquifer units in HR-2 and HR-3

Very few data for the assessment of aquifer parameters have been generated in HR-2 and HR-3. Although boreholes have been drilled at numerous sites, hydrologic testing has been performed at only four locations. These locations include bedrock aquifer tests at test well TSA-1 in Lurance Canyon, and the SWHC Project bedrock monitoring wells SFR-3T and TRN-1 (see Plate II for well locations). In addition, multiple aquifer tests have been performed in the shallow alluvial aquifer underlying the ITRI facility.

No aquifer testing has occurred in several of the geologic units that contain the uppermost regional aquifer. Untested geologic units include the Tertiary conglomerate near the center of HR-2 (Travertine block); the granitic bedrock in northern HR-2 (Manzano block); the shallow portion of the Lower Tertiary unit in southern HR-3; and the Madera limestone in HR-3.

TSA-1 was drilled to a total depth of 300 ft in a combination of granite, quartzite, schist, and metamorphosed sedimentary rock (see Plate II for well location). An aquifer pumping test was accomplished over a depth interval from 180 ft to 300 ft. The lithology in this depth interval was described as "fractured metamorphics." The transmissivity values obtained from this test ranged from 1992 gallons per day per foot (gpd/ft) (drawdown phase) to 1530 gpd/ft (recovery phase)

Table 3.2.4-2. Hydraulic Conductivity for Alluvial Fan Facies of the Santa Fe Group

Data Source	Data Type	Hydraulic Conductivity (ft/day)
Data from Other Publications		
Hawley and Haase (1992)	Estimated for alluvial fan facies	<0.3
KAFB IRP Investigation (USGS 1993)	Slug test	0.08 to 13.0
Water supply well analysis (GMI 1988c)	Pumping test (Ridgecrest well field)	9.66 to 44.7
Data from SNL/NM ER Projects		
Chemical Waste Landfill (IT 1985, SNL/NM 1992, 1995g)	1990 pumping test at MW-2A	0.39
	1990 laboratory analysis of samples from MW-4	0.01 to 10.8
	1985 slug tests at MW-1, MW-2, and MW-3	0.07 to 0.09
	1994 slug tests at BW-3, BW-4, and BW-4A	0.014 to 0.031
	1995 slug tests in MW-1A, MW-2A, MW-3A, MW-5 (upper), and MW-6 (upper)	0.02 to 0.33
	1995 slug test in MW-2B (lower)	6.74
	1995 pumping tests in BW-4A	0.01
	1995 pumping tests in MW-2B (lower)	21.6
	Observation wells MW-5 (lower) and MW-6 (lower) during 1995 pumping test in MW-2B (lower)	25.9 to 27.4
Mixed Waste Landfill (SNL/NM MWL Project Files)	1994 pumping test in MW-4 (upper)	0.072
	1994 pumping test in MW-4 (lower)	1.48
	Recovery data from water-sampling operations (MW-1, MW-2, MW-3, and BW-1)	0.001 to 0.055
LWDS and TA-V (SNL/NM LWDS and TA-V Project Files)	1995 slug tests at LWDS MW-01 and MW-02; TA5 MW-01 and MW-02	0.04 to 2.38
Site-Wide Hydrogeologic Characterization Project (SNL/NM 1995a, Appendix D)	1994 Pumping test at SFR-3P (HR-2)	10.34
	1995 slug test at KAFB-0311	6.15
	1995 analysis of drawdown-recovery data from TA2-NW1-595 (well response due to pumping at KAFB-11)	14.5

Table 3.2.4-3. Hydraulic Conductivity for Perched Aquifer Intervals in Alluvial Fan Facies of the Santa Fe Group

Data Source	Data Type	Hydraulic Conductivity (ft/day)
Data from Other Publications		
KAFB IRP Investigation (USGS 1993)	Slug tests (KAFB IRP monitoring well KAFB-0310)	34.9
Data from SNL/ER Projects		
Site-Wide Hydrogeologic Characterization Project (Appendix D)	1995 pumping test at TJA-2 (drawdown and recovery)	17.6 to 50.2
	1995 slug test at TJA-2	19.3

Table 3.2.4-4. Storage Coefficient Values From Aquifer Tests in the Santa Fe Group

Data Source	Data Type	Storage Coefficient (dimensionless)
Data from Other Publications		
Water supply well analysis (GMI 1988c)	Pumping test analyses (Ridgecrest well field)	0.001
Data from SNL/ER Projects		
Chemical Waste Landfill (SNL/NM 1995g)	1995 pumping test at CWL (MW-5 [lower] and MW-6 [lower])	0.00017 to 0.000033
Site-Wide Hydrogeologic Characterization Project (Appendix D)	1995 analysis of drawdown-recovery data from TA2-NW1-595 (well response due to pumping at KAFB-11)	0.00024

(Geohydrology Associates, Inc. 1987). Using an assumed aquifer thickness of 120 ft (the length of the well completion interval), these transmissivities were converted to hydraulic conductivity values that ranged from 1.70 ft/day to 2.22 ft/day.

In 1994, an aquifer pumping test was accomplished in SWHC Project monitoring well SFR-3T. Although this well is located in HR-2, it was completed in a "Lower Tertiary" sandstone/siltstone bedrock unit below a fault contact. Therefore, the test interval is within a bedrock unit which extends into HR-3. The estimated hydraulic conductivity from this test is 0.00317 ft/day (SNL/NM 1995a).

In 1995, an aquifer pumping test was accomplished in SWHC Project monitoring well TRN-1. This well is completed in the Permian Abo Formation. At the TRN-1 location, this formation includes reddish brown mudstone interbedded with lenticular sandstone beds. The estimated hydraulic conductivity from this test is 0.16 ft/day (see Attachment 4).

Pneumatic slug tests of five monitoring wells and aquifer pumping tests in monitoring well MW-10 were accomplished at the ITRI facility. All the slug tests were performed in wells completed in alluvial material just above weathered Permian siltstone/sandstone units. The calculated hydraulic conductivities from these tests ranged from a low of 6.24 ft/day to a high of 147.10 ft/day (PRC 1990).

The aquifer pumping tests were accomplished in March and April 1993, in monitoring well MW-10, and included several observation wells. Analysis of the data from these tests yielded estimated hydraulic conductivities ranging from 20.6 to 152.2 ft/day (PRC 1993).

Table 3.2.4-5 summarizes shallow alluvium and bedrock hydraulic conductivity data available in HR-2 and HR-3.

No direct data have been obtained to estimate aquifer storativity and porosity for the confined bedrock porous media or fractured rock aquifers on SNL/KAFB. In confined bedrock aquifers, storativity generally ranges from 0.005 to 0.00005 (Freeze and Cherry 1979). Bedrock porosity values are generally lower than the porosity for unconsolidated materials. Expected porosity ranges for different rock types include: sandstone/siltstone, 0.05 to 0.30; mudstone/shale, 0.00 to 0.10; fractured limestone, 0.05 to 0.50; and fractured crystalline rock, 0.00 to 0.10 (Freeze and Cherry 1979).

It is probable that the Paleozoic limestone and Precambrian igneous and metasedimentary bedrock aquifers will be dominated by fracture flow. When fracture density and connectivity is sufficiently high, the fractured media will act hydraulically similar to porous media. However, irregular spacing of fractures and variability of fracture-filling can result in discrete high-permeability flow paths. In addition, fractures that differ in angle and direction will introduce anisotropy to the local flow system. Some limited general characterization is possible for fracture flow systems; e.g., on a regional basis, statistics can be developed from outcrop studies to identify predominant fracture directions and fracture density. However, at a local level, comprehensive site-specific investigations may be required to define local fracture flow. These types of investigations will only become necessary if one or more SNL/NM ER Project sites have contaminated a fractured rock aquifer. A feasibility study on outcrop fracture characterization was reported in SNL/NM (1995a). Observations from this study indicated that a significant percentage of bedrock fractures are open, which suggests that bedrock areas may be effective recharge regions. In addition, fracture orientations vary significantly.

Table 3.2.4-5. Shallow Alluvium and Bedrock Hydraulic Conductivity Data in HR-2 and HR-3

Data Source	Data Type	Hydraulic Conductivity (ft/day)
Data from Other Publications		
Transportation and Safety Division TSA-1 (Geohydrology Associates 1987)	Pumping test	1.70 to 2.22 (fractured granite, quartzite, schist, and metamorphosed sedimentary rock)
ITRI Facility Investigation (PRC 1990, 1993)	Pneumatic slug test	6.24 to 147.1 (shallow alluvium)
	1993 pumping tests	20.6 to 152.2 (shallow alluvium)
Data from SNL/ER Projects		
Site-Wide Hydrogeologic Characterization Project (SNL/NM 1995a, Appendix D)	1994 pumping test at SFR-3T	0.003 (Lower Tertiary sandstone/siltstone)
	1995 pumping test at TRN-1	0.16 (Permian Abo sandstone/siltstone)

3.2.4.3.3 Groundwater flow direction

The direction of groundwater flow through porous and fractured media is controlled by the hydraulic gradient. At a more limited, local scale, the distribution of hydraulic conductivities will affect flow direction. Hydraulic gradient is associated with a specific aquifer, and is determined from measurements of the static water level in wells completed within that specific aquifer unit. The direction of groundwater flow will generally be perpendicular to the potentiometric contours of the measured static-water level.

Lateral groundwater flow

Figure 3.2.4-3 and Plate IV show the potentiometric surface of the SNL/NM and KAFB area for October 1995. (Plate IV shows locations of wells and water-level elevation data used to construct the map.) The potentiometric surface presented on these maps is intended to show flow directions and gradients representative of the uppermost aquifer units. Therefore, to the extent possible, water level data were selected from wells with relatively short screen lengths that spanned the water table (Table 3.2.4-6). Water level measurements were collected and analyzed through the SNL/NM Groundwater Protection Program.

East of the Sandia/Tijeras fault zone, the first encounter of saturated conditions can occur either in the upper unit of the Santa Fe Group, in fractured nonporous bedrock, in porous bedrock (fractured and unfractured), or in shallow alluvial deposits overlying bedrock (see Plate III for identification of geologic units at the groundwater surface). Groundwater elevation contours have been drawn using water level data from wells that are screened in different geologic units. To construct water level elevation contours in this area, the assumption must be made that the geologic units are hydraulically connected and that flow occurs laterally across geologic units and faults. The apparent groundwater-flow direction and gradients shown on Figure 3.2.4-3 seem to indicate that this is the case.

West of the Sandia/Tijeras fault zone, the uppermost aquifer is within the upper unit of the Santa Fe Group, where it ranges from confined (or semiconfined) to unconfined (see Section 3.2.4.1). Figure 3.2.4-3 does not include groundwater potentiometric contours from the uppermost saturated unit in the vicinity of TA-II and the Tijeras Arroyo Golf Course, as did the 1994 potentiometric surface map (SNL/NM 1995a, Plate V). Further study during 1995 has confirmed that the elevated groundwater levels in this area (area of high water elevations is shown outlined on Figure 3.2.4-3) represent a perched groundwater system that is probably not hydraulically connected, at least directly, to the underlying regional Santa Fe Group aquifer system. Figure 3.2.4-4 shows a potentiometric surface map of the perched system, based on data from wells screened in this system. Groundwater elevation contours shown on Figure 3.2.4-3 in the vicinity of TA-II and Tijeras Arroyo Golf Course are based on water level data from wells screened within the regional aquifer system.

As Figure 3.2.4-3 and Plate IV (Table 3.2.4-6) indicate, groundwater flows from bedrock and shallow alluvial aquifers in HR-2 and HR-3, across fault zones, and into the Santa Fe Group aquifer system. East of the Tijeras fault zone, groundwater flow directions and gradients are controlled by topography, aquifer type, and faults. In general, groundwater flows from the northeast to the southwest, oriented with the trend of the mountain front and Lurance Canyon. As groundwater moves west into a more subdued topographic area, where thin alluvial materials are prevalent as a water-bearing unit, the flow direction appears to shift to the west and then crosses the Tijeras fault zone at a northeast angle (parallel to the fault orientation). Probably because of the differences in hydraulic conductivities between the different aquifer units, east of the fault zone the lateral hydraulic gradient varies

Table 3.2.4-6. Groundwater Elevation Data, October/November 1995

Well Name	Date	Time[a] (hr)	Measuring Point Elevation (famsl)	Water Level Measurement (feet below M.P.)[b]	Groundwater Level Elevation (famsl)	Data Source[c]
Kirtland Air Force Base Wells						
Old Water Supply Wells						
KAFB-9	10/31/95	1230	5498.52	541.87	4956.65	SNL/GWPP
KAFB-5	9/95	1000	5433.70	588.25	4845.45	SNL/SWHCP
KAFB IRP Wells						
KAFB-0110	10/31/95	1113	5258.85	388.42	4870.43	SNL/GWPP
KAFB-0114	10/30/95	1437	5317.07	448.63	4868.44	SNL/GWPP
KAFB-0214	10/30/95	1408	5255.96	378.95	4877.01	SNL/GWPP
KAFB-0218	10/30/95	1416	5269.65	393.49	4876.16	SNL/GWPP
KAFB-0310	10/30/95	1437	5416.22	367.01	5049.21	SNL/GWPP
KAFB-0311	11/3/95	0805	5353.48	429.54	4923.94	SNL/SWHCP
KAFB-0417	10/31/95	1029	5314.86	438.85	4876.01	SNL/GWPP
KAFB-0502	10/31/95	0835	5361.21	494.38	4866.83	SNL/GWPP
KAFB-0602	10/31/95	0909	5361.49	312.38	5049.11	SNL/GWPP
KAFB-0609	10/31/95	0926	5361.95	308.12	5053.83	SNL/GWPP
KAFB-0901 (Tij East)	10/30/95	1349	5387.13	478.55	4908.58	SNL/GWPP
KAFB-0902 (Tij West)	10/31/95	1041	5227.30	352.03	4875.27	SNL/GWPP
KAFB-1001	10/30/95	1244	5257.99	361.67	4896.32	SNL/GWPP
KAFB-1002	10/30/95	1249	5253.68	356.34	4897.34	SNL/GWPP
KAFB-1005	10/30/95	1304	5272.55	379.68	4892.87	SNL/GWPP
KAFB-1902	10/31/95	1219	5750.27	88.79	5661.48	SNL/GWPP
New Mexico Environment Department Wells						
MVMWJ	11/6/95		5115.37	217.55	4897.82	SNL/GWPP
MVMWK	11/6/95		5183.38	290.90	4892.48	SNL/GWPP
Sandia National Laboratories Wells						
Environmental Restoration Program						
MWL-BW1	10/30/95	0907	5384.51	463.38	4921.13	SNL/GWPP
MWL-MW2	10/30/95	0914	5377.26	457.98	4919.28	SNL/GWPP
CWL-BW3	10/30/95	0954	5430.23	493.26	4936.97	SNL/GWPP
CWL-MW1A	10/30/95	0947	5418.58	487.46	4931.12	SNL/GWPP
CWL-MW6U	10/30/95	1003	5416.78	482.12	4934.66	SNL/GWPP
CWL-MW6L	10/30/95	1009	5417.13	486.40	4930.73	SNL/GWPP
NWTA-3	10/30/95	1028	5333.81	450.42	4883.39	SNL/GWPP
SWTA-3	10/30/95	1028	5320.57	426.15	4894.42	SNL/GWPP
TA2-NW1-595	9/13/95	1000	5419.27	541.20	4878.07	SNL/SWHCP
TAV-MW2	10/30/95	1051	5424.90	491.83	4933.07	SNL/GWPP

[a]NA = Not available.
[b]M.P. = Measurement point (surveyed).
[c]GWPP = Groundwater Protection Program; SWHCP = Site-Wide Hydrogeologic Characterization Project.

Table 3.2.4-6. Groundwater Elevation Data, October/November 1995 (Concluded)

Well Name	Date	Time[a] (hr)	Measuring Point Elevation (famsl)	Water Level Measurement (feet below M.P.)[b]	Groundwater Level Elevation (famsl)	Data Source[c]
Sandia National Laboratories Wells (Continued)						
East Wells						
EOD	10/30/95	1131	5829.61	143.59	5686.02	SNL/GWPP
Greystone Manor	10/30/95	1104	5820.20	54.36	5765.84	SNL/GWPP
Lake Christian	10/31/95	1156	5712.76	55.65	5657.11	SNL/GWPP
School House	10/31/95	1121	5794.41	95.58	5698.83	SNL/GWPP
Site-Wide Hydrogeologic Characterization Project Wells						
PGS-2 (new)	11/3/95	0750	5405.62	509.60	4896.02	SNL/SWHCP
TJA-2 (Tijeras Arroyo)	11/3/95	0813	5350.53	274.90	5075.63	SNL/SWHCP
TRN-1 (Target Road)	11/3/95	0919	5732.95	89.85	5643.10	SNL/SWHCP
TRS-1S	11/3/95	0911	5776.96	129.39	5647.57	SNL/SWHCP
TRS-1D	11/3/95	0913	5776.96	117.91	5659.05	SNL/SWHCP
TRS-2	11/3/95	0909	5777.09	129.94	5647.15	SNL/SWHCP
MRN-1	10/11/95	1430	5305.87	417.79	4888.08	SNL/SWHCP
MRN-2	11/3/95	1054	5305.51	417.45	4888.06	SNL/SWHCP
PL-1	11/3/95	1030	5332.32	451.71	4880.61	SNL/SWHCP
PL-2	11/3/95	1035	5333.34	454.14	4879.20	SNL/SWHCP
PL-3	11/3/95	1040	5331.97	451.71	4880.26	SNL/SWHCP
SFR-1S	11/3/95	1002	5396.49	90.54	5305.95	SNL/SWHCP
SFR-1D	11/3/95	1000	5396.46	139.62	5256.84	SNL/SWHCP
SFR-2S	11/3/95	0952	5430.10	101.74	5328.36	SNL/SWHCP
SFR-3S	11/3/95	0940	5495.57	163.50	5332.07	SNL/SWHCP
SFR-3P	11/3/95	0940	5496.96	163.50	5333.46	SNL/SWHCP
SFR-3D	11/3/95	0947	5495.27	162.61	5332.66	SNL/SWHCP
SFR-3T	11/3/95	0942	5495.99	80.75	5415.24	SNL/SWHCP
SFR-4P	11/3/95	0933	5570.66	175.41	5395.25	SNL/SWHCP
SFR-4T	11/3/95	0933	5571.28	165.65	5405.63	SNL/SWHCP
AVN-1 (TA- 5)	11/3/95	0840	5440.55	509.32	4931.23	SNL/SWHCP
AVN-2	11/3/95	0845	5439.93	507.20	4932.73	SNL/SWHCP
STW-1 (Solar Tower)	11/3/95	1015	5532.86	154.66	5378.20	SNL/SWHCP
TRE-1 (Thunder Range)	11/3/95	1010	5494.58	174.70	5319.88	SNL/SWHCP
TRE-2	11/3/95	1008	5494.53	165.17	5329.36	SNL/SWHCP
WYO-1	11/3/95	0825	5389.83	507.88	4881.95	SNL/SWHCP
WYO-2	11/3/95	0830	5389.66	271.71	5117.95	SNL/SWHCP
LMF-1	11/3/95	0857	5625.42	347.20	5278.22	SNL/SWHCP
Eubank-1	10/23/95	NA	5457.43	569.06	4888.37	City of ABQ
Inhalation Toxicology Research Institute Wells						
NMED-1	10/23/95	NA	5617.99	89.39	5528.60	ITRI
MW-1	10/23/95	NA	5630.07	96.71	5533.36	ITRI
MW-2	10/23/95	NA	5693.69	136.08	5557.61	ITRI
MW-6	10/23/95	NA	5622.29	88.83	5533.46	ITRI
MW-7	10/23/95	NA	5645.12	111.13	5533.99	ITRI
MW-8	10/23/95	NA	5613.90	80.81	5533.09	ITRI
MW-9	10/23/95	NA	5711.27	153.50	5557.77	ITRI
MW-16	10/23/95	NA	5666.17	112.08	5554.09	ITRI
P-4	10/23/95	NA	5602.98	77.32	5525.66	ITRI
IP-5	10/23/95	NA	5596.37	65.80	5530.57	ITRI

[a]NA = Not available.
[b]M.P. = Measurement point (surveyed).
[c]GWPP = Groundwater Protection Program; SWHCP = Site-Wide Hydrogeologic Characterization Project.

significantly. Lateral hydraulic gradients from well sites Lake Christian to STW and from well sites Target Road South (TRS) to Thunder Range East (TRE) are approximately 0.02 ft/ft. From wells Explosive Ordnance Disposal (EOD) to LMF-1, the hydraulic gradient steepens to 0.12 ft/ft. In general, lateral hydraulic gradients east of the fault zone appear to be approximately equal to, or even greater than, the topographic gradients. At ITRI, groundwater occurs in shallow alluvial sediments that fill a north-trending buried channel carved into the Abo/Yeso formations (PRC 1993, GRAM, Inc. 1995). Groundwater in this area has a low hydraulic gradient (0.002 ft/ft) to the north until it probably mixes with groundwater flowing from the east.

No potentiometric contours are presented for Manzano Base because of the lack of data for this area. There are also very few data directly west of the Sandia fault for this area. Groundwater flow through the granitic terrain of the Manzano Base is probably from the northeast, with flow components to the south into the Arroyo del Coyote drainage. Assuming the granite has a very low permeability, direct precipitation in this area is probably shed mostly from the bedrock through surface runoff, and percolates into the surrounding piedmont sediments. Section 4.2.2.2.1 provides further discussion of the conceptual hydrogeologic model for this area.

The hydraulic gradients across the fault zones are discussed in the following subsection. As shown in Figure 3.2.4-3, groundwater elevations are approximately 300 ft lower west of the Sandia/Tijeras fault complex than east of it. In general, groundwater in the Santa Fe Group aquifer west of the fault complex flows westward until reaching a north- to south-trending, elongated trough, which alters the flow direction to the north. This trough has been created over several decades by the pumping of the water supply wells located along the northern boundary of KAFB (see Plates II and IV), primarily from the ancestral Rio Grande deposits of the upper unit of the Santa Fe Group aquifer. Section 3.2.4.3.4 contains a discussion of long-term water-level declines. In the northern area of SNL/KAFB, monitoring wells show seasonal response to pumping from nearby production wells, creating localized variations in the groundwater flow directions and hydraulic gradients throughout the year. These water supply wells pump much larger volumes in the summer months than in the winter months (SNL/NM 1995i). South of Tijeras Arroyo, seasonal response to water supply pumping is not evident in monitoring wells, although long-term water-level declines remain significant (Section 3.2.4.3.4).

Lateral hydraulic gradients within the uppermost aquifer unit of the Santa Fe Group range from 0.0007 ft/ft for northward flow within the groundwater trough on the western boundary of KAFB to 0.01 ft/ft near active production wells in the northern portion of SNL/KAFB. The lateral hydraulic gradient for most of the uppermost Santa Fe Group aquifer system having a primarily westward flow direction is 0.005 ft/ft (i.e., vicinity of TA-III). Locally, the hydraulic gradients may vary significantly because of the heterogeneous and anisotropic nature of the Santa Fe Group deposits. Additionally, it should be noted that vertical hydraulic gradients are significant in portions of the aquifer system (see the subsection on vertical groundwater flow).

Figure 3.2.4-4 (Table 3.2.4-7) shows the potentiometric surface of the perched groundwater system that underlies the reach of Tijeras Arroyo above its confluence with Arroyo del Coyote. In this area, a relatively high groundwater surface is encountered within the alluvial fan facies in the Santa Fe Group that does not appear to be hydraulically well connected with the regional aquifer system shown in Figure 3.2.4-3. The relatively shallow groundwater may represent a perched aquifer or system of perched aquifers and, possibly, a groundwater mound on the regional aquifer in some areas (SNL/NM 1995a). The lateral and vertical extent of this shallow aquifer system is currently not well known. Based on limited data points within the perched aquifer system, the apparent direction of flow is to the

Table 3.2.4-7. Tijeras Arroyo Shallow Groundwater Elevations, October/November 1995

Well Name	Date	Time (hr)[a]	Measuring Point Elevation (famsl)[a]	Water Level Measurement (feet below M.P.)[b]	Groundwater Level Elevation (famsl)	Data Source[c]
Sandia National Laboratories Wells						
Environmental Restoration Program						
TA2 NW1-325	11/15/95	NA	5418.59	309.63	5107.30	SNL/SWHCP
TA2 SW1-320	11/15/95	NA	5409.18	311.40	5097.43	SNL/SWHCP
TA2 W1	11/13/95	NA	5417.32	320.52	5096.44	SNL/SWHCP
TA2 W19	11/29/95	NA	5348.54	266.80	5081.74	SNL/ER
Site-Wide Hydrogeologic Characterization Project Wells						
PGS-2	11/3/95	0750	5405.62	509.60	4896.02	SNL/SWHCP
TJA-2 (Tijeras Arroyo)	11/3/95	0813	5350.53	274.90	5075.63	SNL/SWHCP
WYO-2	11/3/95	0830	5389.66	271.71	5117.95	SNL/SWHCP
Kirtland Air Force Base Wells						
KAFB-0310	10/30/95	1437	5416.22	367.01	5049.21	SNL/GWPP
KAFB-0602	10/30/95	0909	5361.49	312.38	5049.11	SNL/GWPP
KAFB-0609	10/31/95	0926	5361.95	380.12	5053.83	SNL/GWPP

[a]NA = Not available.
[b]M.P. = Measurement point (surveyed).
[c]SWHCP = Site-Wide Hydrogeologic Characterization Project; ER = SNL/NM Environmental Restoration Project; GWPP = Groundwater Protection Program.

south and southeast. The approximate lateral hydraulic gradient is 0.01 ft/ft (TA2-NW1-325 to TJA-2). There may be several sources of recharge to the perched aquifer system, including direct recharge from Tijeras Arroyo and/or artificial recharge.

Flow across the faults

Water levels of the uppermost aquifer unit on the west side of the Sandia/Tijeras/Hubbell Springs fault complex are approximately 300 ft lower than water levels east of the fault complex; e.g., in the southern part of the SNL/KAFB area, the groundwater flow system crosses the Hubbell Springs and Tijeras faults. As the flow system crosses the Hubbell Springs fault zone, there is an abrupt change in the elevation of the water level in the uppermost aquifer unit of approximately 75 ft over a horizontal distance of approximately 1900 ft. This apparent horizontal gradient of approximately 0.04 ft/ft contrasts with the lower gradients on the east and west of approximately 0.02 and 0.005 ft/ft, respectively. Across the Thunder Range block (see Section 4.2.2.2.3) the horizontal gradient ranges from 0.002 ft/ft near its eastern boundary to approximately 0.01 ft/ft approaching the Tijeras fault. As the flow system crosses the Tijeras fault along the southern boundary of KAFB, between the SFR-1 and Heliport well locations, there is another precipitous change in the water level elevation, this time of approximately 380 ft over the horizontal distance of approximately 6000 ft. This apparent horizontal gradient of approximately 0.06 ft/ft contrasts with the much lower gradient of approximately 0.005 ft/ft west of the fault. The hydraulic-head equipotential lines on either side of the faults generally trend parallel to the faults (see Figure 3.2.4-3). This pattern in equipotentials indicates that there is east to west flow across the faults.

In the southern part of the SNL/KAFB area, the flow system crosses the Hubbell Springs fault zone from the Hubbell Bench area on the east, flows across the Thunder Range block, and then crosses the

Tijeras fault on the west and flows to the west-northwest within the Santa Fe Group aquifer. Water levels in the Thunder Range block (SFR-1D and SFR-2S) are approximately 300 ft lower than the TRN-1 water level in the south-central portion of the Hubbell Bench area and 300 to 400 ft higher than the water level in the CWL monitoring well BW-2, west of the Tijeras fault. The wells in the Thunder Range block and at the CWL are completed in the Santa Fe Group aquifer, whereas the TRN-1 well is completed in a confined bedrock aquifer in the Permian Abo Formation. The chemistry in all four monitoring wells is remarkably similar. In particular, bromide (Br^-), chloride (Cl^-), and sulfate, chemical species that would be expected to be most conservative (moves with groundwater and is nonreactive), have very similar concentrations in samples from these wells (see Attachment 2). For the concentrations of non-reactive, conservative tracer species to change, one of the following must occur:

1. the waters must be mixed with waters having a different species concentration,
2. the species in the source water must be concentrated by evaporation, or
3. the species must be added in the absence of additional water (i.e., dissolution of minerals containing these species).

If concentrations do not change over distance, none of these effects have occurred. The similarity of concentrations of Cl^-, Br^-, and SO_4^{-2} in wells TRN-1 (Permian, Abo Formation), SFR-1D and SFR-2S (Santa Fe Group), and CWL-BW2 (Santa Fe Group) indicates that none of the three effects listed above has occurred to a significant degree. These similarities in concentrations and the hydraulic gradients strongly support the conceptual model of waters moving from east to west across the fault with minimal mixing. If mixing of waters from other sources is occurring, either this mixing is not apparent at the sampled depths, or the mixed-in waters have very similar concentrations.

Vertical groundwater flow

Vertical groundwater flow within and between aquifers is indicated when there is a vertical change in hydraulic head at a single location. Tables 3.2.4-8 through 3.2.4-12 summarize hydraulic head data available at locations where there are water level measurements at different vertical positions at a single location. The vertical gradient at these locations is estimated by dividing the difference in water level between the individual monitoring wells by the vertical distance between the mid-points of the respective well screens.

Hydrogeologic Region 1 — In the alluvial fan facies of the Santa Fe Group aquifer underlying the TA-III/TA-V area, observed hydraulic head differences indicate that there is downward vertical flow between the uppermost fine-grained (and low hydraulic conductivity) unit and the underlying sandy intervals (Table 3.2.4-8). In general, this downward gradient ranges between 0.02 and 0.07 ft/ft; however, at the MWL, this gradient is much higher, ranging from 0.11 to 0.88 ft/ft, depending on which sand interval in MWL MW-4 is compared to the uppermost unit completed in MWL MW-1. These very high gradients suggest that the fine-grained completion interval in MW-1 may be reacting more slowly to water supply pumping than the deeper completion intervals in MW-4.

In the fluvial facies of the Santa Fe Group aquifer, there is a low downward gradient ranging from 0.001 to 0.008 ft/ft (Table 3.2.4-9). This low gradient suggests that the fluvial facies has a good vertical hydraulic connection.

Several locations near Tijeras Arroyo have monitoring wells in both the uppermost perched aquifer and the underlying regional aquifer (Table 3.2.4-10). The vertical hydraulic gradients at these locations are approximately 0.9 ft/ft in a downward direction.

Hydrogeologic Region 2 — In this region, vertical gradient data are available in the Thunder Range block (see Section 4.2.2.2.3) both within the Santa Fe Group, and between the Santa Fe Group and the underlying Tertiary bedrock (Table 3.2.4-11) (SNL/NM 1995a). In the Santa Fe Group, the vertical gradient is downward and ranges from a low of 0.006 at monitoring wells SFR-3S/SFR-3D to a high of 0.25 ft/ft at monitoring wells SFR-1S/SFR-1D. The high vertical gradient at the SFR-1 location is between the unconfined upper aquifer (SFR-1S) and an underlying confined aquifer (SFR-1D) (SNL/NM 1995a). At the SFR-3 location where hydraulic head data are available for both the bedrock (SFR-3T) and the Santa Fe Group (SFR-3P), the gradient is upward from the bedrock into the Santa Fe Group at 0.15 ft/ft.

Table 3.2.4-8. Vertical Hydraulic Gradients in Alluvial Fan Facies of the Santa Fe Group in Hydrogeologic Region 1

Well	Groundwater Elevation (famsl)	Well	Groundwater Elevation (famsl)	Distance Between Screen Centers (ft)	Difference in Water Levels (ft)	Vertical Gradient and Direction	Geologic Unit
CWL MW-6U	4935.48 (8/26/94)	CWL MW-6L	4932.16 (8/26/94)	62	3.67	0.059, downward	SFG[a] alluvial fan facies
CWL MW-5U	4935.73 (8/26/94)	CWL MW-5L	4931.56 (8/26/94)	56	3.78	0.068, downward	SFG alluvial fan facies
CWL MW-2BU	4936.60 (8/26/94)	CWL MW-2BL	4933.22 (8/26/94)	57	3.75	0.066, downward	SFG alluvial fan facies
AVN-1	4931.2 (11/3/95)	AVN-2	4932.7 (11/3/95)	75	1.5	0.020, downward	SFG alluvial fan facies
MWL MW-1	4921.20 (4/14/95)	MWL MW-4 (lower zone)	4896.00 (4/14/95)	63.5	25.20	0.40, downward	SFG alluvial fan facies
MWL MW-1	4921.20 (4/14/95)	WL MW-4 (upper zone)	4900.43 (4/14/95)	23.5	20.77	0.88, downward	SFG alluvial fan facies
MWL MW-4 (lower zone)	4896.00 (4/14/95)	MWL MW-4 (upper zone)	4900.43 (4/14/95)	40	4.43	0.11, downward	SFG alluvial fan facies

[a]SFG = Santa Fe Group regional aquifer.

Table 3.2.4-9. Vertical Hydraulic Gradients in the Fluvial Facies of the Santa Fe Group in Hydrogeologic Region 1

Well	Groundwater Elevation (famsl)	Well	Groundwater Elevation (famsl)	Distance Between Screen Centers (ft)	Difference in Water Levels (ft)	Vertical Gradient and Direction	Geologic Unit
PL-2	4879.2 (11/03/95)	PL-3	4880.3 (11/03/95)	132	1.1	0.008, downward	SFG[a] fluvial facies
MRN-1	4888.6 (08/29/95)	MRN-2	4888.8 (08/29/95)	142	0.20	0.001, downward	SFG fluvial facies

[a]SFG = Santa Fe Group regional aquifer.

Table 3.2.4-10. Vertical Hydraulic Gradients Between the Shallow Perched Aquifer System and the Santa Fe Group Regional Aquifer in the Vicinity of Tijeras Arroyo

Well	Groundwater Elevation (famsl)	Well	Groundwater Elevation (famsl)	Distance Between Screen Centers (ft)	Difference in Water Levels (ft)	Vertical Gradient and Direction	Geologic Unit
TJA-2	5075.6 (11/3/95)	KAFB-0311	4923.9 (11/3/95)	160	151.7	0.95, downward	Between SFG[a] and perched aquifer
WYO-2	5118.0 (11/3/95)	WYO-1	4882.0 (11/3/95)	260	236.2	0.91, downward	Between SFG and perched aquifer
TA2-NW1-325	5109.6 (10/7/94)	TA2-NW1-595	4889.7 (10/7/94)	230	219.9	0.96, downward	Between SFG and perched aquifer

[a]SFG = Santa Fe Group regional aquifer.

Table 3.2.4-11. Vertical Hydraulic Gradients in Hydrogeologic Region 2

Well	Groundwater Elevation (famsl)	Well	Groundwater Elevation (famsl)	Distance Between Screen Centers (ft)	Difference in Water Levels (ft)	Vertical Gradient and Direction	Geologic Unit
SFR-1S	5306.0 (11/3/95)	SFR-1D	5256.8 (11/3/95)	196	49.2	0.25, downward	SFG[a] alluvial fan facies
TRE-2	5329.4 (11/3/95)	TRE-1	5319.9 (11/3/95)	115	9.5	0.08, downward	SFG alluvial fan facies
SFR-3S	5333.43 (11/3/95)	SFR-3D	5332.66	135	0.8	0.006, downward	SFG alluvial fan facies
SFR-3P	5333.5 (11/3/95)	SFR-3T	5415.2 (11/3/95)	538	81.7	0.15, upward	Between SFG and bedrock

[a]SFG = Santa Fe Group regional aquifer.

<u>Hydrogeologic Region 3</u> — In this region, vertical gradient data are available in one set of monitoring wells completed in the Madera Formation (Table 3.2.4-12). These data indicate that at this location there is an upward vertical gradient between Madera limestone fractured zones of 0.11 ft/ft (Appendix C).

Table 3.2.4-12. Vertical Hydraulic Gradient in Hydrogeologic Region 3

Well	Groundwater Elevation (famsl)	Well	Groundwater Elevation (famsl)	Distance Between Screen Centers (ft)	Difference in Water Levels (ft)	Vertical Gradient and Direction	Geologic Unit
TRS-1S	5647.9 (11/3/95)	TRS-1D	5659.1 (11/3/95)	101	11.2	0.11, upward	Madera Formation

An analysis of the impact of the vertical gradient in the alluvial fan facies has been accomplished by developing a vertical cross-section flow net to analyze horizontal and vertical components of flow between the CWL on the upgradient southeast corner of TA-III and the MRN wells west of TA-III (Figure 3.2.4-5). Because of the heterogeneous and anisotropic condition of the aquifer, the method of Fogg and Senger was used to generate the flow net automatically (Fogg and Senger 1985). This method consists of modeling the cross section using MODFLOW (McDonald and Harbaugh 1988) and applying appropriate boundary conditions as specified by Fogg and Senger (1985). The procedures used to perform the analysis as well as the results of the analysis are described in the following sections.

Aquifer stratigraphy and hydraulic conductivity — As noted in cross section D to D' of Attachment 1, the aquifer along this transect beneath TA-III consists of a package of anisotropic and heterogeneous sediments. These sediment layers are approximately horizontal. On the east side of the cross section, fine-grained alluvial fan sediments grade into fine- to coarse-grained ancestral Rio Grande sediments. The contact between these distinct hydraulic units is located approximately 1400 ft west of the CWL.

The uppermost water-bearing unit beneath the CWL consists of approximately 38 ft of silty clay. The majority of monitoring wells at the site are screened in this unit. Three sand layers, each approximately 10 to 15 ft thick, are present within the upper 135 ft of the aquifer. Three monitoring wells are screened across the middle of these sand layers. The sand layers are separated by 10- to 25-ft-thick clay units. Near the base of the cross section, a 10-ft-thick clay layer confines an approximately 5-ft-thick sand layer.

For the sand layers beneath the CWL, a horizontal hydraulic conductivity of 21.6 ft/day and a vertical hydraulic conductivity of 0.2 ft/day were calculated. These values were derived from the average of the drawdown and recovery data collected during the aquifer test at CWL MW-2B and an assumed anisotropy of 100, as suggested for this type of aquifer in Freeze and Cherry (1979). Aquifer test results from MRN-1 representative of ancestral Rio Grande sediments indicated a hydraulic conductivity value of 46.7 ft/day.

The horizontal and vertical conductivities of the clay layers were 1.5×10^{-2} and 2.8×10^{-4} ft/day, respectively. These values were derived from the results of the analysis of soil samples. The samples used for this part of the analysis were collected within the clay layer between 480 and 520 ft below ground surface (bgs) at the CWL. As suggested by Freeze and Cherry (1979), the weighted arithmetic mean and harmonic mean of the laboratory-derived saturated conductivity were used to estimate the horizontal and vertical conductivity, respectively. Table 3.2.4-13 presents the hydraulic data associated with each sediment unit.

Table 3.2.4-13. Calculated Horizontal (K_h) and Vertical (K_v) Hydraulic Conductivities

Sediment Type (USGS)	Horizontal Conductivity (K_h) in ft/day	Vertical Conductivity (K_v) in ft/day	Equivalent K[a] in ft/day	Horizontal Gradient[b]	Vertical Gradient
Ancestral Rio Grande sand	46.7[c]	0.47[d]	4.2	0.003	0.001
Alluvial fan silty clay	0.015[e]	0.000282[f]	2.1×10^{-3}	0.006	0.064[g]
Alluvial fan sand	21.6[c]	0.216[d]	2.16	0.005	0.064[g]

[a]Equivalent conductivity is the SQRT (K_h*K_v) as suggested by Fogg and Senger (1985).
[b]Horizontal gradient along the groundwater table is calculated from the potential drop between wells MW-6U and SWTA-3, and SWTA-3 and MRN-1. Horizontal gradient along the base of the model was calculated between MW-6L and SWTA-3, and SWTA-3 and MRN-2.
[c]Horizontal conductivity of the sand facies was calculated from the pump test analysis on MW-2B and MRN-1. It is the arithmetic average of the drawdown and recovery tests.
[d]Vertical conductivity of the sand was estimated from literature values suggested by Freeze and Cherry (1979).
[e]Horizontal conductivity of the silty clay is the geometric average of laboratory saturated conductivity values from soil samples collected between 145 and 158 m (480 and 520 ft) bgs.
[f]Vertical conductivity of the silty clay is the harmonic average of laboratory saturated conductivity values from soil samples collected between 145 and 158 m (480 and 520 ft) bgs.
[g]Vertical gradient for the alluvial fan sediments beneath the CWL is the arithmetic average of the gradient calculated using data at the midsection of well screen in the deep and shallow wells at MW-6, MW-5, and MW-2B. Vertical gradient in the ancestral Rio Grande at MRN was measured to be negligible.

Model flow field — For this application, a two-dimensional grid was used to simulate steady-state groundwater flow paths along a cross section between CWL MW-6 and MRN-1. No transient effects, such as drawdown due to pumping, were modeled directly; however, the vertical gradient observed in wells screened across the fine-grained alluvial fan layers was incorporated into the model. This downward gradient may be a result of groundwater pumping north of TA-III. This cross section was selected for analysis because it was oriented approximately parallel to the ambient flow field. The MODFLOW model grid consisted of 70 rows and 100 columns. Row and column spacing were 2 and 100 ft, respectively. This large aspect ratio was necessary to model the silty clay layers that are relatively thin and grade into the ancestral Rio Grande. The dimensions of the modeled area were 10,000 ft long by 140 ft deep.

In the model domain, it was assumed that two fine-grained alluvial-fan sedimentary layers beneath the CWL were wedge shaped and pinched out approximately 1400 ft west of the CWL. These layers were assigned a horizontal and vertical hydraulic conductivity of 0.015 ft/day and 0.0028 ft/day, respectively. The interbedded, alluvial-fan sand layers were grouped into one layer and assigned the same hydraulic conductivity as the ancestral Rio Grande sediments because the K values for each sediment were similar, approximately 22 and 48 ft/day, respectively. The horizontal and vertical conductivity of these sediments was 46.7 and 0.47 ft/day, respectively. Figure 3.2.4-5 presents the model cross-section hydrostratigraphy.

Boundary conditions — Measured hydraulic heads in CWL MW-6U, MW-6L, and MRN-1/2 were used to develop the boundary conditions in the model. To calculate lines of equipotential, hydraulic heads were prescribed along the bottom and sides of the model domain. Given the negligible recharge rates between arroyos, the groundwater surface was modeled as a no-flow boundary. The prescribed groundwater elevations used for these calculations were measured on October 30, 1995 (CWL wells) and November 3, 1995 (MRN wells). The averaged gradient of 0.004 ft/ft was approximated along the base of the model domain by calculating the gradient between MW-6L and MRN-2.

The prescribed heads along the east side of the model domain were based on interpolation and extrapolation of the average vertical gradient measured in CWL monitoring wells MW-6, MW-2B, and MW-5 during August 1994. The average vertical gradient was 0.064. Based on October and November 1995 groundwater elevations, the prescribed head values input into the model ranged between 4937.8 feet above mean sea level (famsl) at the groundwater surface to 4929.0 famsl at the base of the section along the east boundary of the model. Along the west boundary of the model domain, a constant head value of 4886.9 famsl was used because no appreciable vertical difference in head was measured between MRN-1 and MRN-2.

To calculate streamlines, prescribed streamlines were specified along each side of the model domain. The streamline at each boundary cell was calculated in accordance with the procedures outlined by Fogg and Senger (1985) using the Dirichlet boundary condition. Table 3.2.4-8 summarizes the vertical gradient data measured at the CWL monitoring wells and used as model input.

Flow-net results — Figure 3.2.4-5 presents the model-generated flow net. Because of the anisotropic hydrostratigraphy and the vertical exaggeration of scale, the streamlines and equipotentials are not orthogonal to each other. Accordingly, the illustrated cells do not form curvilinear square elements. Nonetheless, the flow net describes the direction and amount of flow across the section.

Within the fine-grained alluvial-fan facies, the equipotentials show a downward vertical gradient. This is consistent with field observations at the CWL and MWL. The direction of the streamlines within these sediments shows that water entering the system within the alluvium has a substantial downward component of flow. After the water reaches the sand layers, these streamlines refract upward and approximately parallel the contact between the sand and silty clay layers.

Due to the low hydraulic conductivity within the alluvium, very little water flows through it relative to the amount of groundwater that flows through the alluvial fan sand facies and ancestral Rio Grande. To show streamlines in the fine-grained alluvium, a contour interval of 0.003 ft^3/day was used. In comparison, the contour interval of streamlines in the sandy sediments was 6 ft^3/day.

The model predicts a slight upward vertical gradient in the sand layer between and below the wedges of alluvial silty clay. The streamlines show that nearly all the water from upgradient recharge sources, such as HR-2 and HR-3, enters the modeled area through the sand layers. West of the contact between the alluvial fan and ancestral Rio Grande sediments, groundwater flow is approximately horizontal with a slight upward vertical gradient.

3.2.4.3.4 Regional groundwater-level trends

Groundwater withdrawal by water supply wells for the City of Albuquerque and KAFB has resulted in significant changes to the groundwater flow regime in the Santa Fe Group aquifer system over the past 30 yr as discharge exceeds recharge for this region of the Albuquerque basin (Thorn et al. 1993). Groundwater flow at SNL/KAFB has been altered from a principally westward flow direction to northwestward and northward flow directions along the western and northern portions of KAFB (Figure 3.2.4-3, Plate IV).

Water level declines have been occurring within the Albuquerque basin since the 1960s, when significant increases in groundwater withdrawal began. Basin-wide declines from steady-state conditions have been estimated to range from 20 to 160 ft (Thorne et al. 1993). The greatest declines are to the east of the eastern limit of fluvial deposits of the ancestral Rio Grande.

Since the mid-1980s, water levels have been collected from monitoring wells on SNL/KAFB (SNL/NM 1995i). Hydrographs from these data indicate groundwater levels are declining at rates of between 0.2 to 3.0 ft/yr within the upper unit of the Santa Fe Group aquifer system (HR-1). Figure 3.2.4-6 shows groundwater level declines in feet per year for SNL/KAFB. On KAFB, the rate of water level declines generally increases westward from the Sandia/Tijeras fault zone and northward near water-supply production wells (Figure 3.2.4-6). Based on estimates of steady-state conditions by Thorn et al., groundwater has declined from 60 to 140 ft across the base (Thorn et al. 1993). Groundwater level surveillance by SNL/NM since approximately 1990 (SNL/NM 1995i) indicates that wells completed west of the eastern extent of fluvial deposits have water level declines of 1.0 to 3.0 ft/yr, whereas wells on the east display declines of 1.0 ft or less per year.

These groundwater declines represent only the upper 100 ft or less of the upper unit of the Santa Fe Group aquifer because most of the wells on SNL/KAFB are water-quality monitoring wells and have short screen lengths in comparison to the thickness of the aquifer. This may explain the discrepancy between the higher declines noted by Thorn et al. (1993) east of the eastern limit of fluvial deposits and the lower decline rate at SNL/KAFB (Figure 3.2.4-6) also on the east side of the eastern limit of fluvial deposits. Monitoring wells in this area are generally screened in finer-grained materials of the alluvial fan facies and respond more slowly to groundwater withdrawals. Water level declines in deeper coarser-grained units may be greater than those indicated by the water level trends for the existing monitoring wells. Also, most monitoring wells within SNL/KAFB, especially on the eastern half of HR-1, are not close to active water supply wells and are, therefore, less influenced by these wells.

Hydrographs for wells within HR-2 and HR-3 show that water levels in these regions are not currently affected by water supply production within the Santa Fe Group aquifer system. Although water levels show significant seasonal variability, the long-term trends show that water levels have remained relatively constant or are only increasing slightly. Wells in the shallow alluvium near Lake Christian show an increase in water levels of 0.4 to 0.6 ft/yr since 1991, perhaps from higher-than-average precipitation over the past 10 yr (see Section 3.2.1). Wells completed in bedrock and shallow alluvium in Lurance Canyon show minimal increases in the long-term water-level trends. These wells may have a faster response time to meteorological changes and may have already equilibrated with the higher precipitation rate.

Wells screened in the perched aquifer system underlying Tijeras Arroyo do not show the same pattern of water level decline as wells screened in the deeper aquifer zones. This indicates that the perched system is probably not directly connected to the regional aquifer system. Insufficient data are available to adequately evaluate water level trends in most of the wells screened in the perched aquifer system, with the exception of the Tijeras Arroyo Golf Course wells and KAFB-0310. Water levels in these wells are increasing at a rate of approximately 2 ft/yr.

3.2.4.3.5 Hydrogeochemistry

The DOE Grand Junction Projects Office, and its contractor, Rust Geotech, studied local hydrogeochemical data to determine groundwater origins (e.g., recharge areas) and flow paths. Analyses included "mass balance" and "reaction path" modeling (see Attachment 2 for a description of these models). Data used in this study, collected regularly by the SNL/NM ER Project and SNL/NM Groundwater Protection Program, included a total of nine samplings during 1992, 1993, and 1994 (Rust Geotech 1995). Data were first screened for completeness and outliers (any chemical species deviating significantly from typical values at that site). If any outliers were present, all data from that sampling of a specific site were rejected from the analysis. Attachment 2 contains the complete report generated by this activity, and principal findings are summarized below. The locations of sites and wells described below are shown on Plate II.

Assemblage of sufficient geochemical information to produce a unique, subsurface model, capable of defining groundwater flow paths and recharge areas, would be a monumental task (see Section 6 of Attachment 2). Data available for the hydrogeochemical study presented in Attachment 2 were limited in quantity. Samples were available from 24 wells, several of which wells were in clusters, and most water was sampled from the shallowest aquifer. Little information was available about the chemical composition of solid-phase aquifer components. Consequently, conclusions drawn from geochemistry are of limited, localized significance. Inferences drawn from geochemistry include:

- Wells KAFB-10 and CWL-BW2 may have high Cl^- as a result of deeper screens; KAFB-10 is also sampled without purging, which could contribute to high Cl^-.

- Sulfate in water from the Santa Fe Group wells shows no obvious trends across the basin, except that sulfate is lowest at three wells furthest northwest. The lack of a trend is evident even in the east-west line of South Fence Road wells screened in the Santa Fe Group (SFR-1, SFR-2, and SFR-3P).

- Water from South Fence Road wells screened in the footwall of a fault (wells SFR-3T and SFR-4T, both screened in the deeper, lower Tertiary Formation) differ significantly from those screened in the overlying Santa Fe Group. A 3-day pumping test performed in SFR-3P similarly indicated there is no significant connection between these formations at this location (i.e., vertical hydraulic conductivity is less than one-tenth horizontal hydraulic conductivity) (SNL/NM 1995a).

- Water from KAFB-0602 (Golf Course South) and MVMW-J wells appears to have relatively high levels of nitrate plus nitrite, presumably caused by surface applications of nitrogen fertilizers.

- Waters from Coyote Springs and the EOD well appear to both be from a deeper water source than other waters in the basin. Differences in calcium and bicarbonate can be explained by exsolution of carbon dioxide gas and precipitation of calcite ($CaCO_3$) at Coyote Springs. Higher concentrations of Br^- and Cl^- at Coyote Springs can be accounted for by evaporation at that site.

- Groundwaters from School House and Greystone wells near Coyote Springs and at Sol se Mete Spring have deuterium values which suggest that their source is rainwater infiltration. In contrast, deuterium is depleted at Coyote Springs and the EOD well, suggesting direct infiltration is not the primary source of these waters.

- Mass-balance methods suggest that a small portion of the water in the Santa Fe Group may come from saline fluids migrating along the basin boundary faults.

- Elevated Cl^- concentrations of water from the South Fence Road wells screened in the Santa Fe Group suggest an influence from high salinity fluids moving along basin faults. Overall major ion chemistry within these wells suggests a common origin for their waters. These waters are quite similar to those present in the TRN-1 well, which is screened in the Permian Abo Formation, and is located about 1½ - 2 miles NE of the South Fence Road wells.

- Reaction-path modeling shows that, if water from SFR-3T flows through a reactive zone containing calcite, sodium (Na)-rich exchangeable clays, and a small amount of halite, a groundwater similar in composition to SFR-4T well water would evolve; however, flow in this direction is against the prevailing groundwater heads. This potential pathway will require additional analysis and/or correction.

- Concentrations of deuterium and oxygen-18 in groundwaters in the Santa Fe Group show two distinct groups. Relative to concentrations of deuterium and oxygen-18 in groundwater at SNL/KAFB, three of the most northwesterly wells are isotopically light (i.e., depleted in deuterium and oxygen-18), whereas all other wells to the east are isotopically heavy (i.e., enriched in deuterium and oxygen-18). Coupled with piezometric heads and other information, this suggests that groundwater near the northwestern boundary of KAFB may be partially composed of Rio Grande waters.

- Coyote Springs and EOD Hill waters share similarities in Cl^-, Br^-, and Na^+ concentrations and ionic strength, and differ from all other groundwater studied at SNL/KAFB. Coyote Springs and EOD Hill waters could be in communication if the alluvial fill of the paleochannel on the eastern edge of EOD Hill extends to the present-day Arroyo del Coyote east of Coyote Springs (Attachment 1, Figure 4.0.1).

It has recently become apparent to investigators at SNL/KAFB that geochemical evaluation of groundwater may be affected by apparently innocuous acts on the surface. For example, one area has been identified where man-caused blockage of an arroyo channel has created a source of artificial aquifer recharge. This blockage is located just within the eastern edge of TA-III in an unnamed arroyo, and was identified by strange behavior of a stream gage at that site. The occurrence of recharge at this site is indicated by a total absence of caliche deposits beneath the channel surface, very wet soils within the depths examined (0 to 9.5 ft), and by stream gaging data that suggest ponding depths in excess of 1 ft occur frequently (Appendix A). Observations suggest that the ponding is more often caused by local runoff from roads and development rather than by natural runoff from upstream portions of the arroyo. The channel upstream of this site is underlain by massive caliche at depths less than 1 ft.

Where man-caused recharge occurs over an area where recharge previously did not occur, excess concentrations of evaporitic materials may be washed from the soil and into the aquifer below. For example, Cl^- concentrations in surface soils at the CWL indicate that an accumulation of Cl^- from several thousand years of precipitation is present in the upper few feet of soil (Appendix B). These concentrations are equal to more than 0.5 kg of Cl^- per cubic meter of soil; deeper soils (i.e., to approximately 18 m in this study) have approximately half this concentration. If these soil concentrations continue to the water table (some 150 m lower), approximately 40 kg of Cl^- are present in the vadose zone per square meter of surface area. A small quantity of aquifer recharge water passing through a hypothetical 1-m^2 column of this soil would leach out much of this Cl^-. This quantity (40 kg) of Cl^- is sufficient to increase the Cl^- concentration in 56,800 ft^3 of groundwater by 25 mg/l. This quantity of groundwater occupies 284,000 ft^3 of an aquifer with a porosity of 20%, or an area approximately 533 ft on a side and 1 ft thick. The actual volume of soil that would be leached by recharging waters would be orders of magnitude larger than the 1-m^2 column hypothesized here, so the quantity of potentially effected groundwater would be very much larger. The concentration of Cl^- (and some other chemical species, such as Br^- or Na^+) in the leachate would be very high, so that other, nonleached species (e.g., tritium) present in the recharge may not appear to increase in the affected groundwater because the recharged water volume is relatively small compared to the volume in the aquifer.

The date that this particular channel was blocked is unknown. Whether recharge from the blocked channel has reached the aquifer beneath it is also unknown; if the recharge has reached the aquifer, unusual concentrations of some chemical species will be present in the water over some area in that vicinity.

A large hole dug to create an observation mound west of the sled track (near well MRN-1) will be a much larger source of recharge when that portion of the arroyo finally flows; however, it appears that this has not occurred since the hole was excavated more than 15 yr ago. Other such man-made recharge locations, have not been identified, although they probably exist; one possibility is a crater at the Pick Axe site.

3.2.4.4 Role of groundwater in contaminant transport

Solutes may leach from sources through the vadose zone as liquids or vapors into the groundwater. As such, the groundwater provides a significant pathway to receptors. The vadose zone beneath most SWMUs at SNL/KAFB is greater than 300 ft thick and recharge rates are estimated to be small, so nonaqueous-phase liquid transport is likely to be negligible; however, certain wastes may reach the groundwater via vapor transport and/or dissolution in aqueous-phase waste (such as leaching from septic tank systems). As solutes migrate from the source areas, the concentrations become more dilute through mixing with groundwater. Reactive wastes, such as metals and certain organic compounds, may sorb to aquifer materials and travel less quickly than the ambient groundwater. Nonreactive wastes, such as salts, do not strongly sorb to the aquifer matrix and advance with the average groundwater velocity.

3.2.5 Groundwater Modeling

The SWHC Project has developed a three-dimensional numerical groundwater flow model for the regional aquifer underlying HR-1. The model was used to explore and test, in a quantitative fashion, the conceptual model of the hydrogeology of HR-1 developed by the Site-Wide Hydrogeologic Characterization Project (SWHC). In addition, it will help the Environmental Restoration (ER) Project to develop a quantitative understanding of groundwater pathways across the SNL/KAFB area.

3.2.5.1 SNL/KAFB Model Selection and Approach

The SNL/KAFB model consists of a groundwater flow model only. The flow model is based upon the Albuquerque basin model developed by Kernodle et al. (1995). The computer code MODFLOW, written by the U.S. Geological Survey, was used to simulate the three-dimensional flow of groundwater beneath HR-1. MODFLOW is the most widely used groundwater flow model in the world, is the computer code used in the ABM, and has been successfully used in analyses performed in the area by the U.S. Geological Survey and others to construct and calibrate both steady-state and transient models. Groundwater levels have been declining since the 1960's in the KAFB area, and it was necessary to consider large-scale trends in water levels, which the ABM does. The SNL/KAFB portion of the basin model was removed from the ABM by using a modified telescopic mesh refinement approach in which the flows across the boundaries and the aquifer properties were used to create a smaller, easier to work with and faster to execute model. The submodel grid remained the same as the ABM grid.

The approach taken in this analysis follows a general protocol that has been developed for model application (Anderson and Woessner, 1992; ASTM Standard Guide D5447-93, "Application of a Ground-Water Flow Model to a Site-Specific Problem"). This protocol includes code selection issues, model conceptualization and design, calibration, sensitivity analysis, prediction, and reporting. Figure 3.1 in Attachment 4 illustrates the steps in the protocol. The verification and postaudit steps are typically not performed. Verification is the comparison of independent model prediction to data not used in calibration. It is often impossible to verify a model because usually only one set of field data is available, which is needed for calibration (Anderson and Woessner, 1992). A postaudit is the comparison of model prediction to reality some period of time (often several years) after the modeled action is implemented.

3.2.5.2 Boundary Conditions, Aquifer Parameters, and Calibration Data

Information from the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Resources, other public sources, and the Sandia National Laboratories Site-Wide Hydrogeologic Characterization (SWHC) Project were used to develop the conceptual model of the hydrogeology in the vicinity of the site. The SNL/KAFB model builds upon the work presented in the SWHC 1993 (SNL/NM 1994a), 1994 (SNL/NM 1995a), and this annual report and is consistent with the U.S. Environmental Protection Agency (EPA) modeling recommendations noted in their review of the 1994 SWHC annual report. The conceptual model separated the sediments into alluvial fan and ancestral Rio Grande fluvial deposits, arranged in complex intergradational architectures. Pumping test results, water level measurements, and geological mapping from the SWHC were used to determine the distribution of facies and their hydraulic properties in the model.

In order to remove the SNL/KAFB area from the ABM, boundary conditions had to be developed that related the subarea to the regional system. The procedure consisted of calculating the groundwater flow in each cell on the boundary of the SNL/KAFB submodel within the ABM. This calculation was performed by running the ABM and computing the time-step weighted average of the flow across each cell boundary during each stress period. One average value was computed for each cell during each stress period from 1980 to 1995. A comparison of the calculated heads in the ABM and SNL/KAFB indicates that the difference between heads is less than 1 ft for all layers. Thus the boundaries specified for the SNL/KAFB model reproduces similar values as the ABM, and allowed the use of a smaller area rather than the full ABM. Other boundaries (the drains, rivers, wells, and evapotranspiration) were unchanged from the ABM.

Calibration targets are a set of field measured values, typically groundwater hydraulic heads, to which model predicted values are compared. The goal in selecting calibration targets is to define a set of measurements that are reliable and spatially distributed throughout the model area. Comparisons should be made between point measurements of hydraulic heads rather than maps of these heads, because the contour lines are the result of interpretation of data points and are not considered basic data in and of themselves. The groundwater flow model should be true to the essential features of the conceptual model and not to their representation (ASTM Standard Guide D5490-93, "Comparing Ground-Water Flow Model Simulations to Site-Specific Information").

These measurements have an inherent error component due to instrument and sampling scale limitations. It is important to define the level of plausible uncertainty in order to know when the model calibration is as good as warranted by the data, and to set goals in the context of statistical measures. Table 3.2.5-1 summarizes the goals established for calibration (see Attachment 4) and what was achieved during calibration for the USGS model and the 2 implementations of the SWHC conceptual model.

Table 3.2.5-1. Calibration Criteria and Achieved Values

Criteria	Goal	Baseline USGS Model	SWHC CM, USGS Tijeras Arroyo Flow	SWHC CM, SWHC Tijeras Arroyo Flow
Mean error, ME (ft)	9.4	-7.6	-2.91	4.23
Error standard deviation, SD (ft)	9.4	9.65	6.31	6.35
Ratio of SD to total observed head change	10%	10.2 %	6.7 %	6.7 %
Sum of errors squared, SS (ft^2)	110,000	230,000	74,400	89,800

3.2.5.3 Model Calibration

Calibration of a groundwater flow model is the process of adjusting model parameters until the model reproduces field-measured values of head and flow rates. Successful calibration of a flow model to observed heads and flow directions enables the model to be used in the prediction of groundwater flow paths and heads, and allows conclusions to be drawn about the conceptual model.

Model calibration is judged by quantitatively analyzing the difference (called a residual hereafter) between observed and model-computed values. Several statistical and graphical methods are used to assess the model calibration. These statistics and methods are described in greater detail in ASTM (American Society for Testing Materials) standards D5490-93 "Comparing Ground-Water Flow Model Simulations to Site-Specific Information" and in Attachment 4.

The fit of the USGS model to the SNL/KAFB potentiometric data was fair to poor, and did not adequately replicate the major features observed in the area. Incorporation of geologic data collected during the SWHC Project was able to largely resolve these discrepancies. The model was calibrated to conditions from January 1980 to March 1995. The quantitative calibration goals that were established for this analysis were met. The model of the SNL/KAFB was substantially modified over the initial configuration constructed by the USGS. Figures 4.2 and 4.6 in Attachment 4 show a histogram of residuals and observed versus simulated potentials, respectively.

The modifications made to the USGS ABM included addition of a long north-south strip of axial channel deposits, extending much further than in the ABM. In addition, SWHC Project estimates of hydraulic conductivity of alluvial fan material along the mountains were much lower than in the ABM, as was recharge from infiltration along Tijeras Arroyo. In the ABM recharge along Tijeras Arroyo is over an order of magnitude higher than that estimated by the SWHC Project. Two models were calibrated to bracket the conceptual uncertainty caused by this difference. In the first, the recharge rate specified by the USGS was maintained, and the model modified to reflect the SNL/KAFB conceptual model. For the second model, recharge along Tijeras Arroyo was reduced to the value estimated by the SWHC Project. The high recharge case required high hydraulic conductivities in the alluvial fan material where Tijeras Arroyo enters SNL/KAFB. The values were not unreasonable when compared with SWHC data from Technical Area 2, but the model still exhibited a pronounced overprediction (too much water) in the area, which suggested that the Tijeras Arroyo flow rate in the ABM may be too high. In the low recharge case, hydraulic conductivities in the area where Tijeras Arroyo enters SNL/KAFB were very low.

3.2.5.4 Conclusions

The model that the SWHC Project has developed for the HR-1 area has been calibrated to a degree believed to be reasonable in light of the supporting data and the overall dynamic flow system. The model boundary conditions are entirely dependent on basin-wide influences from the City of Albuquerque's municipal pumping; consequently the predictive power of the SWHC model can be no better than the ABM, which, as discussed in Attachment 4, is probably low. Assumed boundary conditions could be used to make forecasts, but given the future uncertainty in potentiometric levels due to radical changes in City of Albuquerque operations it is felt that there is little value in this approach.

The sensitivity of the model to two relatively poorly known parameters, initial head and specific yield, has a deleterious effect on the predictive capability of any model of the basin because it is possible to have compensating errors in parameter values. In the case of initial heads, it is simply not possible to overcome the data deficiency from earlier in this century. However, the purpose of this analysis was comparative, and the difference in representations the important result. The numerical representation of the conceptual model developed by the SWHC Project appears to adequately represent reality.

3.3 REFERENCES

Abbott, J. C., and L. B. Goodwin, 1995. A Spectacular Exposure of the Tijeras Fault, with Evidence for Quaternary Motion: New Mexico Geological Society, Guidebook 46, pp. 117-125.

Anderholm, S. K., 1988. Ground-Water Geochemistry of the Albuquerque-Belen Basin, Central New Mexico, U.S. Geological Survey - Water-Resources Investigations Report 86-4094, U.S. Geological Survey, 110 pp.

Anderson, M. P., and W. W. Woessner, 1992. Applied Groundwater Modeling, Simulation of Flow and Advective Transport. San Diego, CA: Academic Press, Inc., pp. 381.

Baars, D. L., 1961. Permian Strata of Central New Mexico: New Mexico Geological Society, Guidebook 12, pp. 113-120.

Bartel, L. C., C. W. Ray, R. D. Jacobson, and P. M. Drozda, 1981. Use of CSAMT Technique to Map a Fault on Kirtland Air Force Base. Geothermal Studies at Kirtland Air Force Base, New Mexico, Appendix A. SAND81-0852, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Birkeland, P. W., 1984. Soils and Geomorphology. New York, New York: Oxford University Press, 371 pp.

Bjorklund, L. J., and B. W. Maxwell, 1961. Availability of Ground Water in the Albuquerque Area, Bernalillo and Sandoval Counties, New Mexico. New Mexico State Engineer Technical Report 21, 117 pp.

Brookins, D. A., 1982. Radiometric Ages of Precambrian Rocks from Central New Mexico: New Mexico Geologic Society, Guidebook 33, pp. 187-189.

Bryan, K., and F. T. McCann, 1937. The Ceja del Rio Puerco: A Border Feature of the Basin and Range Province in New Mexico, Part I: Stratigraphy and Structure: Journal of Geology, Vol. 45, No. 8, pp. 801-828.

Calvin, W. J., J. R. Connolly, D. L. Edwards, M. Parchman, and L. A. Woodward, 1982. Precambrian Stratigraphy of Manzanita and Northern Manzano Mountains, New Mexico Geological Society Guidebook, 33rd Field Conference, Albuquerque Country II, pp. 191-196.

Cather, S. M., and B. D. Johnson, 1984. Eocene Tectonics and Depositional Setting of West-Central New Mexico and Eastern Arizona: New Mexico Bureau of Mines and Mineral Resources, Circular 192, 33 pp.

Chapin, C. E., and S. M. Cather, 1994. Tectonic Setting of the Axial Basins of the Northern and Central Rio Grande Rift, in Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America, Special Paper 291, pp. 5-25.

Connolly, J. R., 1982. Structure and Metamorphism in the Precambrian Cibola Gneiss and Tijeras Greenstone, Bernalillo County, New Mexico: New Mexico Geological Society, Guidebook 33, p. 197-202.

Connolly, J. R., L. A. Woodward, and J. W. Hawley, 1982. Road-Log Segment I-A: Albuquerque to Tijeras Canyon: New Mexico Geological Society, Guidebook 33, pp. 2-8.

Cordell, L. E., 1978. Regional Geophysical Setting of the Rio Grande Rift: Geological Society of America Bulletin, Vol. 89, No. 7, pp. 1073-1090.

Dane, J. H., and F. J. Molz, 1991. Physical Measurements in Subsurface Hydrology, Reviews of Geophysics, Supplement. U.S. National Report to International Union of Geodesy and Geophysics 1987-1990, pp. 270-279.

Faust, C. R., P. N. Sims, C. P. Spalding, P. F. Andersen, B. H. Lester, M. G. Shupe, and A. Harrover, 1994. FTWORK: Groundwater Flow and Solute Transport in Three Dimensions. GeoTrans.

Fischer, E. E., J. J. Rote, and J. P. Borland, 1984. Rainfall-Runoff Data in the Albuquerque, New Mexico, Metropolitan Area, 1976-1983. USGS open file report 84-448, Albuquerque, NM.

Fogg, G. E., and R. K. Senger, 1985. Automatic Generation of Flow Nets with Conventional Groundwater Modeling Algorithms. Groundwater, May-June, Vol. 23, No. 3.

Foutz, W. L., 1994. Summary of Field Operations at Canyon Drilling Location CYN-BH1, CYN-BH2, and CYN-BH3. SNL/NM memorandum to Lee Broulliard, Canyons Area Assistant Task Leader.

Freeze, R. A., and J. A. Cherry, 1979. Groundwater. Englewood Cliffs, New Jersey: Prentice-Hall.

GMI, 1988a. Groundwater Management Incorporated. Pumping Test Data Analysis: Burton Well Field, City of Albuquerque, New Mexico. Unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

GMI, 1988b. Groundwater Management Incorporated. Pumping Test Data Analysis: Miles Road Well Field, City of Albuquerque, New Mexico. Unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

GMI, 1988c. Groundwater Management Incorporated. Pumping Test Data Analysis: Ridgecrest Well Field, City of Albuquerque, New Mexico. Unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

GRAM, Inc., 1995. Conceptual Geologic Model of the Sandia National Laboratories and Kirtland Air Force Base, New Mexico. Prepared for Sandia National Laboratories/New Mexico Environmental Restoration Program.

Galusha, T., 1966. The Zia Sand Formation, New Early to Medial Miocene Beds in New Mexico: American Museum Novitates, No. 2271, 12 pp.

Gee, G. W., and D. Hillel, 1988. Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods, Hydrological Processes, Vol. 2, pp. 255-266.

Gee, G. W., C. T. Kincaid, R. J. Lenhard, and C. S. Simmons, 1991. Recent Studies of Flow and Transport in the Vadose Zone, Reviews of Geophysics, Supplement. U.S. National Report to International Union of Geodesy and Geophysics 1987-1990, pp. 227-239.

Geohydrology Associates, Inc., 1987. Drilling Summary of the TSA Exploratory Well No. 1. Unpublished report to U.S. Department of Energy, December 1987.

Gile, L. H., F. F. Peterson, and R. B. Grossman, 1965. The K Horizon - Master Soil Horizon of Carbonate Accumulation: Soil Science, Vol. 99, No. 2, pp. 74-82.

Goodrich, M., 1992. Report on a Surface Gravity Survey for Fault Delineation and Hydrogeologic Characterization. International Technology Corporation contractor report prepared for Sandia National Laboratories, New Mexico, Albuquerque, NM.

Grant, P. R., 1982. Geothermal Potential in the Albuquerque Area, New Mexico, New Mexico Geological Society Guidebook, 33rd Field Conference, Albuquerque Country II, pp. 325-331.

Hacker, L. W., 1977. Soil Survey of Bernalillo County and Parts of Sandoval and Valencia Counties, New Mexico: USDA Soil Conservation Service, 101 pp.

Haneberg, W., 1995. Steady State Groundwater Flow Across Idealized Faults. Water Resources Research, Vol. 31, No. 7, July, pp. 1815-1820.

Hawley, J. W., 1986. Physiographic Provinces of New Mexico, in Williams, J. L., ed., New Mexico in Maps. University of New Mexico, Albuquerque, pp. 23-27.

Hawley, J. W., 1995. Personal communication with Dirk Van Hart, New Mexico Bureau of Mines and Mineral Resources.

Hawley, J. W., and C. S. Haase, 1992. Hydrogeologic Framework of the Northern Albuquerque Basin. New Mexico Bureau of Mines and Mineral Resources Open-File Report 387, Socorro, NM, 165 pp.

Hawley, J. W., and D. W. Love. 1991. Quaternary and Neogene Landscape Evolution: A Transect Across the Colorado Plateau and Basin and Range Provinces in West-Central and Central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 137, pp. 105-148.

IT, 1985. International Technology Corporation. RCRA Interim Status Groundwater Monitoring Plan, Chemical Waste Landfill. Prepared for Sandia National Laboratories, Albuquerque, NM.

IT, 1992. International Technology Corporation. Geologic Mapping of Sanitary Sewer Line Excavation, Southern Sandia National Laboratories, Albuquerque, NM. SWHC/4.0001, contractor report to SNL Environmental Restoration Program, IT, Albuquerque, NM.

Ingersoll, R. V., W. Cavazza, W. S. Baldridge, and M. Shafiqullah, 1990. Cenozoic Sedimentation and Paleotectonics of North-Central New Mexico: Implications for Initiation and Evolution of the Rio Grande Rift: Geological Society of America Bulletin, Vol. 102, pp. 1280-1296.

Kelley, V. C., 1963. Geologic Map of the Sandia Mountains and Vicinity, New Mexico. New Mexico Bureau of Mines and Mineral Resources Geologic Map 18, scale 1:48,000.

Kelley, V. C., 1977. Geology of the Albuquerque Basin, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Memoir 33, Socorro, NM, 60 pp.

Kelley, V. C., 1982. Diverse Geology of the Hubbell Bench, Albuquerque Basin, New Mexico: New Mexico Geological Society, Guidebook 33, pp. 159-160.

Kelley, V. C., and S. A. Northrop, 1975. Geology of the Sandia Mountains and Vicinity, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Memoir 29, Socorro, NM, 135 pp.

Kernodle, J. M., and W. B. Scott, 1986. Three-Dimensional Model Simulation of Transient Ground-Water Flow in the Albuquerque-Belen Basin, New Mexico. Water Resources Investigation Report 84-4353, U.S. Geological Survey.

Kernodle, J. M., R. S. Miller, and W. B. Scott, 1987. Three-Dimensional Model Simulation of Transient Ground-Water Flow in the Albuquerque-Belen Basin, New Mexico. Water Resources Investigation Report 86-4194, U.S. Geological Survey.

Kernodle, J. M., D. P. McAda, and C. R. Thorn, 1995. Simulation of Ground-Water Flow in the Albuquerque Basin, Central New Mexico, 1901-1994, with Projections to 2020. Water Resources Investigations Report 94-4251, U.S. Geological Survey.

Kirby, E., and K. Karlstrom, 1994. New Geologic Map of Precambrian Rocks in the Tijeras 7.5' Quadrangle: Implications from the Proterozoic to the Tertiary. Proceedings Volume, 1994 New Mexico Geological Society Spring Meeting (Abstract), p.46.

Kues, B. S., S. G. Lucas, and R. V. Ingersoll, 1982. Lexicon of Phanerozoic Stratigraphic Names Used in the Albuquerque Area: New Mexico Geological Society, Guidebook 33, pp. 125-138.

Lambert, P. W., 1968. Quaternary Stratigraphy of the Albuquerque Area, New Mexico (Ph D. Thesis). University of New Mexico, Albuquerque, NM, 329 pp.

Lewis, C. J., and W. S. Baldridge, 1994. Crustal Extension in the Rio Grande Rift, New Mexico: Half-Grabens, Accommodation Zones, and Shoulder Uplifts in the Ladron Peak-Sierra Lucero Area, in Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America Special Publication 291, pp. 135-155.

Lisenbee, A. L., L. A. Woodward, and J. R. Connolly, 1979. Tijeras-Cañoncito Fault System - A Major Zone of Recurrent Movement in North-Central New Mexico: New Mexico Geological Society, Guidebook 30, pp. 89-99.

Lozinsky, R. P., 1988. Stratigraphy, Sedimentology, and Sand Petrology of the Santa Fe Group and Pre-Santa Fe Tertiary Deposits in the Albuquerque Basin, Central New Mexico (Ph.D. Thesis). New Mexico Institute of Mining and Technology, Socorro, NM, 298 pp.

Lozinsky, R. P., 1994. Cenozoic Stratigraphy, Sandstone Petrology, and Depositional History of the Albuquerque Basin, Central New Mexico, in Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting. Geological Society America Special Paper 291, pp. 73-81.

Lozinsky, R. P., and R. H. Tedford, 1991. Geology and Paleontology of the Santa Fe Group, Southwestern Albuquerque Basin, Valencia County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 132, 35 pp.

Lozinsky, R. P., J. W. Hawley, and D. W. Love, 1991. Geologic Overview and Pliocene-Quaternary History of the Albuquerque Basin, Central New Mexico: New Mexico Bureau of Mines and Minerals Resources Bulletin 137, pp. 157-162.

Lucas, S. G., 1982. Vertebrate Paleontology, Stratigraphy and Biostratigraphy of Eocene Galisteo Formation, North-Central New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 186, 34 pp.

MICROPALEO, 1993. Micropaleo Consultants, Inc. Palynological Analysis - Five Samples from Shallow Wells, Kirkland [*sic*] Air Force Base. Contractor report prepared for GRAM, Inc., August 2, 1993.

Machette, M. N., 1978. Dating of Quaternary Faults in the Southwestern United States by Using Buried Calcic Paleosols: U.S. Geologic Survey Journal of Research, Vol. 6, pp. 369-381.

Machette, M. N., 1982. Quaternary and Pliocene Faults in the La Jencia and Southern Part of the Albuquerque-Belen Basins, New Mexico: Evidence of Fault History from Fault-Scarp Morphology and Quaternary Geology: New Mexico Geological Society, Guidebook 33, pp. 161-169.

Martinez, R., 1989. Summary of Laramide Orogeny in New Mexico, in Lorenz, J. C. and Lucas, S. G., eds., Energy Frontiers in the Rockies: AAPG-SEPM-EMD Rocky Mountain Section Companion Volume, pp. 171-176.

May, S. J., S. A. Kelley, and L. R. Russell, 1994. Footwall Unloading and Rift Shoulder Uplifts in the Albuquerque Basin: Their Relation to Syn-Rift Fanglomerates and Apatite Fission-Track Ages: Geological Society of America Special Paper 291, pp. 125-134.

May, S. J., and L. R. Russell, 1994. Thickness of the Syn-Rift Santa Fe Group in the Albuquerque Basin and Its Relation to Structural Style, in Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting. Geological Society of America Special Paper 291, pp. 113-123.

Maynard, S. R., L. A. Woodward, and D. L. Giles, 1991. Tectonics, Intrusive Rocks, and Mineralization of the San Pedro-Ortiz Porphyry Belt, North-Central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 137, pp. 57-69.

McCord, J. T., and D. B. Stephens, 1987. Lateral Moisture Movement on Sandy Hillslope in the Apparent Absence of an Impeding Layer: Hydrologic Processes, Vol. 1, No. 3, pp. 225-238.

McDonald, M. G., and A. W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Techniques of Water-Resources Investigations 06-A1, U.S. Geological Survey, 576 pp.

McTigue, D. L., and C. Stein, 1990. Retention Curves and Saturated Hydraulic Conductivities of Area III Alluvium. Sandia National Laboratories internal memorandum, January 16, 1990, to distribution, from McTigue, Division 1511, and Stein, Division 6233, 21 pp.

Metzker, K. D., R. L. Gold, and R. P. Thomas, 1993. Rainfall and Runoff Data in the Albuquerque, New Mexico, Metropolitan Area, 1984-1988.

Miller, J. F., R. H. Frederick, and R. J. Tracey, 1973. Precipitation-Frequency Atlas of the Western United States, Volume IV -- New Mexico. National Oceanic and Atmospheric Administration (NOAA) Atlas 2, 43 pp.

Myers, D. A., 1973. The Upper Paleozoic Madera Group in the Manzano Mountains, New Mexico: U.S. Geological Survey Bulletin 1372-F, 13 pp.

Myers, D. A., 1982. Stratigraphic Summary of Pennsylvanian and Lower Permian Rocks, Manzano Mountains, New Mexico: New Mexico Geological Society, Guidebook 33, pp. 233-237.

Myers, D. A., and E. J. McKay, 1970. Geologic Map of the Mount Washington Quadrangle, Bernalillo and Valencia Counties, New Mexico. U.S. Geological Survey Geologic Quadrangle Map GQ-886, scale 1:24,000.

Myers, D. A., and E. J. McKay, 1971. Geologic Map of the Bosque Peak Quadrangle, Torrance, Valencia, and Bernalillo Counties, New Mexico. U.S. Geological Survey Geologic Quadrangle Map GQ-948, scale 1:24,000.

Myers, D. A., and E. J. McKay, 1976. Geologic Map of the North End of the Manzano Mountains, Tijeras and Sedillo Quadrangles, Bernalillo County, New Mexico. U.S. Geological Survey Miscellaneous Geologic Investigations Map I-968, scale 1:24,000.

NOAA, 1990. National Oceanographic and Atmospheric Administration. Local Climatological Data, Annual Summary with Comparative Data, Albuquerque, NM.

Olsen, O., M. H. Hall, and M. H. Plagge, 1970. Wind Data for the Albuquerque Area, SC-M-70-144, Sandia National Laboratories/New Mexico, Albuquerque, NM.

PRC, 1990. PRC Environmental Management, Inc. ITRI Lagoon Hydrogeological Study. Unpublished report prepared for the Lovelace Inhalation Toxicology Research Institute, Albuquerque, NM.

PRC, 1993. PRC Environmental Management, Inc. Alluvial Aquifer Characterization Study. Unpublished report prepared for the Lovelace Inhalation Toxicology Research Institute, Albuquerque, NM.

Parsons, A. M., J. T. McCord, R. P. Thomas, and M. Furaus, 1993 (in press). Using a Geographic Information System to Select Vadose Zone Hydrogeologic Settings for Guiding Site Characterization. SAND93-1843, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Persaud, N., and P. J. Wierenga, 1982. Solute Interactions and Transport in Soils from Waste Disposal Sites at Sandia Laboratories. Prepared by the Department of Agronomy, New Mexico State University, Las Cruces, NM, 237 pp.

Phillips, F. M., J. L. Mattick, and T. A. Duval, 1988. Chlorine-36 and Tritium from Nuclear Weapons Fallout as Tracers for Long-Term Liquid and Vapor Movement in Desert Soils: Water Resources Research, Vol. 24, No. 11, pp. 1677-1891.

Reiche, P., 1949. Geology of the Manzanita and North Manzano Mountains, New Mexico: Geological Society of America Bulletin, Vol. 60, pp. 1183-1212.

Riddle, L., and P. R. Grant, 1981. Geothermal Studies at Kirtland Air Force Base, Albuquerque, New Mexico. SAND81-0852, Sandia National Laboratories/New Mexico, Albuquerque, NM, May 1981.

Russell, L. R., and S. Snelson, 1990. Structural Style and Tectonic Evolution of the Albuquerque Basin Segment of the Rio Grande Rift, in Pinet, B., and Bois, C., eds., Potential for Deep Seismic Profiling for Hydrocarbon Exploration: Editions Technip, Paris, French Petroleum Institute Research Conference Proceedings, pp. 175-207.

Russell, L. R., and S. Snelson, 1994. Structure and Tectonics of the Albuquerque Basin Segment of the Rio Grande Rift: Insights from the Reflection Seismic Data, in Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting. Geological Society of America Special Paper 291, pp. 83-112.

Rust Geotech, 1995. Geochemical Study of Groundwater at Sandia National Laboratories/New Mexico and Kirtland Air Force Base. GJPO-WMP-96, prepared for U.S. Department of Energy, Albuquerque Operations Office, Grand Junction Projects Office, Grand Junction, CO, October 1995.

SAIC, 1985. Science Applications International Corporation. Installation Restoration Program Phase II: Confirmation/Quantification Stage 1 for Kirtland Air Force Base, Albuquerque, New Mexico. Unpublished report for the U.S. Air Force, March 1985.

SNL/NM, 1991. Sandia National Laboratories/New Mexico. Groundwater Monitoring Program Calendar Year 1990 Annual Report. Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1992. Sandia National Laboratories/New Mexico. Chemical Waste Landfill Final Closure Plan and Postclosure Permit Application. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1993a. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1992 Annual Report. SAND93-0681, Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1993b. Sandia National Laboratories/New Mexico. Mixed Waste Landfill Phase 2 RFI Work Plan. Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994a. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1993 Annual Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994b. Sandia National Laboratories/New Mexico. Groundwater Protection Program Calendar Year 1993 Annual Groundwater Monitoring Report. Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995a. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1994 Annual Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995b. Sandia National Laboratories/New Mexico. Analysis of Instantaneous Profile Test Data from Soils near the Mixed Waste Landfill, Technical Area 3, Sandia National Laboratories/New Mexico. SAND95-1637, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995c. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Hydrology Testing Laboratory Results for Projects SFR-1D, CWL-MW6, MWL-MW4, and LWDS-MW1. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995d. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Hydrology Testing Laboratory Results for Projects I-25 Persons Section, TA-2-NW1-595, MRN-2, CWL-BW4, CWL-MW2B, CWL-MW4, and CWL-MW5. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995e. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Hollow Stem Auger Project Hydrology Testing Laboratory Results, Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995f. Sandia National Laboratories/New Mexico. Hydrology Testing Laboratory Results for TA-I RFI Background Soils Investigation. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995g. Sandia National Laboratories/New Mexico. Chemical Waste Landfill Ground-Water Assessment Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995h. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Soil Pit Project Hydrology Testing Laboratory Results. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995i. Sandia National Laboratories/New Mexico. Groundwater Protection Program Calendar Year 1994 Annual Groundwater Monitoring Report. Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, in press. Sandia National Laboratories/New Mexico. Mixed Waste Landfill Phase II RCRA Facility Investigation Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Sigma, 1984. Sigma Geoservices, Inc. Seismic Reflection Survey on Kirtland Air Force Base, New Mexico. Contractor report prepared for U.S. Army Corps of Engineers, April 1984.

Soil Survey Staff, 1992. Keys to Soil Taxonomy. SMSS Technical Monograph No. 19, 5th Edition, Virginia: Pocahontas Press, 540 pp.

Spiegal, Z., and B. Baldwin, 1963. Geology and Water Resources of the Santa Fe Area, New Mexico. U.S. Geological Survey Water-Supply Paper 1525, 258 pp.

Stephens and Associates, 1990a. Laboratory Analysis of Soil Hydraulic Properties from the MW-4 CWL Monitoring Well. Unpublished report prepared for Ecology and Environment, Inc., Albuquerque, NM.

Stephens and Associates, 1990b. Laboratory Analysis of Soil Hydraulic Properties from the MW-4 CWL Monitoring Well (130.75 feet to 253.33 feet). Unpublished report prepared for Ecology and Environment, Inc., Albuquerque, NM.

Stephens, D. B., and R. G. Knowlton, Jr., 1986. Soil-Water Movement and Recharge Through Sand at a Semiarid Site in New Mexico: Water Resources Research, Vol. 22, pp. 881-889.

Tedford, R. H., 1982. Neogene Stratigraphy of the Northwestern Albuquerque Basin: New Mexico Geological Society, Guidebook 33, pp. 273-278.

Thomas, C. L., 1995. Infiltration and Quality of Water for Two Arroyo Channels, Albuquerque, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 95-4070, Albuquerque, NM.

Thorn, C. R., D. P. McAda, and J. M. Kernodle, 1993. Geohydrologic Framework and Water Resources Conditions in the Albuquerque Basin, Central New Mexico. Water Resources Investigation Report 93-4149, U.S. Geological Survey, Albuquerque, NM, 106 pp.

Titus, F. G., 1963. Geology and Ground-Water Conditions in Eastern Valencia County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 41, Socorro, NM.

Titus, F. G., 1980. Ground-Water in the Sandia and Northern Manzano Mountains, New Mexico. New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 5, 66 pp.

USDA, 1992. U.S. Department of Agriculture. David Goodrich, U.S. Department of Agriculture, Tucson, Arizona, personal communication with Jim McCord.

USGS, 1990. U.S. Geological Survey. Water Resources Data for New Mexico, Water-Year 1989. U.S. Geological Survey Water Data Report NM-89-1, Albuquerque, NM.

USGS, 1991. U.S. Geological Survey. Water Resources Data for New Mexico, Water-Year 1990. U.S. Geological Survey Water Data Report NM-90-1, Albuquerque, NM.

USGS, 1992a. U.S. Geological Survey. Water Resources Data for New Mexico, Water-Year 1991. U.S. Geological Survey Water Data Report NM-91-1, Albuquerque, NM.

USGS, 1992b. U.S. Geological Survey. Personal communication by Grace Haggerty with S. K. Anderholm, U.S. Geological Survey.

USGS, 1993. U.S. Geological Survey. Installation Restoration Program, Stage 2A, RI/FS Technical Report for Kirtland Air Force Base, USGS, Water Resources Division, Albuquerque, NM.

Waltemeyer, S. D., 1986. Techniques for Estimating Flood-Flow Frequency for Unregulated Streams in New Mexico, USGS Water-Resources Investigations Report 86-4104, Albuquerque, NM.

Ward, D. S., D. R. Buss, J. W. Mercer, and S. S. Hughes, 1987. Evaluation of a Groundwater Corrective Action at the Chem-Dyne Hazardous Waste Site Using a Telescopic Mesh Refinement Modeling Approach: WRR, Vol. 23, No. 4, pp. 603-617.

Wells, S. G., K. I. Kelson, and C. M. Menges, 1987. Quaternary Evolution of Fluvial Systems in the Northern Rio Grande Rift, New Mexico and Colorado: Implications for Entrenchment and Integration of Drainage Systems, in Menges, C. M., ed., Quaternary Tectonics, Landform Evolution, Soil Chronologies and Glacial Deposits - Northern Rio Grande Rift of New Mexico. Friends of the Pleistocene - Rocky Mountain Cell, Field Trip Guidebook, pp. 55-70.

Wilson, L. G., L. G. Everett, and S. J. Cullen, 1994. Handbook of Vadose Zone Monitoring and Characterization, Boca Raton, Lewis Publishers/CRC Press.

Woodward, L. A., 1977. Rate of Crustal Extension Across the Rio Grande Rift Near Albuquerque, New Mexico: Geology, Vol. 5, pp. 269-272.

4.0 HYDROGEOLOGIC CONCEPTUAL MODEL

This section includes an elementary discussion of the different elements of the SNL/KAFB geologic framework and hydrologic processes (Section 4.1), a detailed description of elements of the CM (Section 4.2), and an identification of the major uncertainties in the CM (Section 4.3).

4.1 GENERAL GEOLOGIC FRAMEWORK AND HYDROLOGIC PROCESSES

A valid CM provides a realistic simplification of a complex physical system and the processes that take place within it. A CM is necessary because any hydrogeologic system is too complex to be described and treated exactly as it is (Bear 1979). The CM for the SNL/KAFB area should capture all the critical features of the geologic framework and integrate all the important hydrologic processes.

The general geologic framework includes the following elements:

- Stratigraphy
- Sedimentology
- Structural geology and tectonics
- Geochemistry
- Pedology
- Geomorphology

Some important hydrologic processes and conditions that are related to contaminant transport include:

- Interception
- Infiltration
- Recharge
- Surface runoff
- Soil-water storage
- Evapotranspiration
- Soil-water potential
- Water flow in the unsaturated zone
- Groundwater flow in the saturated zone

4.1.1 General Geologic Framework

The geologic framework that is required to define a hydrogeologic CM includes many separate elements. These elements vary in character (between locations, both vertically and horizontally), in scale (from the macroscopic to the microscopic), and through time. Perhaps the best manner in which to introduce the various elements is to summarize the diverse branches of the earth sciences that are used to define and describe the elements. This summary is derived from the following sources: Ramsey (1967), Whitten and Brooks (1976), Spencer (1977), Reading (1978), Brownlow (1979), Birkeland (1984), Ritter (1986), Bates and Jackson (1987), and Catt (1988).

Branches of the earth sciences that are commonly used to define the geologic elements of a hydrogeologic CM include stratigraphy, sedimentology, structural geology and tectonics, geochemistry, pedology (the science of soils), and geomorphology. Other branches not discussed, such as paleontology (the study of fossils and ancient life) and geophysics (the study of physical phenomena of and within the earth), can also help in understanding relationships within the hydrogeologic CM.

Stratigraphy is the study of the sequence of layered rock units, the character of these units, and the correlation of units among different localities. The stratigraphic sequence found on SNL/KAFB is presented in Figure 3.1.2-1 and discussed in Section 3.1. Several major natural "breaks" or unconformities exist between units of different ages at SNL/KAFB. These unconformities form the basis for dividing the stratigraphic discussion of Section 3.1.2 into packages of differing strata of Precambrian (Section 3.1.2.1) through Quaternary (Section 3.1.2.6) age. An unconformity develops during a period of time in which no sediment is deposited, when sediment deposition is interrupted, or when erosion occurs. The plane of unconformity may be a surface of weathering, erosion, or non-deposition. It may be parallel to the top of the rock sequence or cut across the rock sequence at an angle. Subsequent earth movements may have folded or faulted the unconformity. In general, unconformities indicate a temporary or permanent change in the geologic setting or conditions. Commonly, the hydrogeologic properties above and below the unconformity are much different because of this change in geologic setting or conditions with time. An example of an unconformity that affects the hydrogeologic model for SNL/KAFB is the regional unconformity that underlies the Santa Fe Group. In this report, the various geologic units below this contact are called bedrock and include sedimentary, igneous, and metamorphic rocks. The units above this unconformity are grouped as basin-fill sediments and include the Santa Fe Group and younger alluvial sediments.

Sedimentology includes the study of processes by which sedimentary rocks and structures are formed. All surficial units on KAFB (except portions of the bedrock) are sediments and sedimentary rocks (e.g., sandstones, siltstones, shales, and conglomerates) that are derived from either the mountains to the east (e.g., the Llano de Sandia and Llano del Manzano Provinces) or from the upper Rio Grande drainage basin of northern New Mexico and southern Colorado (e.g., the Rio Grande Province) (see Section 3.1.3). Subsurface units of the Santa Fe Group have these same two different source regions. Santa Fe Group and post-Santa Fe Group strata form the basin fill of the Albuquerque Basin and include alluvial fan deposits that are derived from the east, fluvial deposits derived from the north, and locally thick, playa-lake and eolian deposits of the central portions of the basin. Units of the Santa Fe Group originally formed as unconsolidated material or sediments that, through time, have undergone diagenesis or the process of converting unconsolidated sediments to coherent sedimentary rocks.

Sedimentological features can include the external form or geometry of the bedding, such as bedding thickness, bedding configuration, bedding continuity, and bedding connectivity, or the internal structures within beds, such as laminations and systematic changes in grain size (e.g., grading). These features are used by geologists to define lithofacies (i.e., rock types with similar sedimentary rock type, mineral content, sedimentary structures, bedding characteristics, and fossil content), to infer depositional environments, and to evaluate secondary alteration of the units during or after diagenesis. The same features affect the flow of groundwater through the vadose and saturated zones beneath KAFB.

Much of the lower Tertiary through upper Paleozoic sequence of KAFB is also sedimentary rocks (Sections 3.1.2.2 through 3.1.2.4). Upper Paleozoic units are marine to nonmarine interstratified carbonates and clastic units. Upper Cretaceous lithologies include shales and sandstones with coaly interbeds (see Section 3.1.2.3), whereas lower Tertiary or Paleogene units include sandstones, siltstones, shales, and fanglomerates of the Baca Formation. Overlying these units and locally underlying the Santa Fe Group is the informally named Unit of Isleta #2 Well, a fine- to coarse-grained sandstone with claystones and silty interbeds.

Structural geology and tectonics involve the studies of structural features of or within the earth's crust. The tectonic history of KAFB, at least in the past 20 to 30 million years, has been dominated by the evolution of the central Rio Grande rift (see Section 3.1.1). Faults, such as the Tijeras, Sandia, and Hubbell Springs faults on KAFB, involve differential movement of the upper several kilometers of the earth's crust. KAFB lies on an accommodation zone, the Tijeras fault zone, that separates asymmetric subsidence within the northern and southern portions of the Albuquerque Basin. Recent mapping has provided insight into the interrelationships between these faults. For example, a small crossover structure, a localized graben across which extension has occurred, has been found to connect the northern end of the Hubbell Springs fault to the Tijeras fault zone (Section 3.1.1.1).

Faults also are major factors in groundwater flow. Hubbell Springs is located immediately to the south of KAFB and lies on the Hubbell Springs fault. Coyote Springs is located along the trace of the Coyote Springs fault. A major change in depth of the water table is seen across the Tijeras/Sandia/Hubbell Springs faults complex (Section 3.2.4.2).

Geologic structures of a smaller scale can also influence the hydrogeologic conceptual model. For example, fractures in bedrock could provide preferential flowpaths for the local hydrogeologic system. Particularly in the bedrock-dominated Manzanita Mountains, fractures control groundwater flow. Preferential orientations for fractures and other structural features within the bedrock will facilitate flow in certain directions for groundwater and, if applicable, contaminants.

Geochemistry deals with the abundance and distribution of elements within the earth. The science can be applied both to lithologic units and to the fluids within those lithologic units. Geochemistry seeks to determine the composition of the earth and its parts and to discover the laws that control the distribution of individual elements within the earth.

Pedology, or the study of soils, concentrates on the accumulation of loose, weathered material that covers much of the land surface to a depth that can range from a fraction of an inch to many feet. Soils typically contain discrete horizons or layers subparallel to the overlying geomorphic surface that represent concentrations of different secondary minerals (e.g., carbonates and clays). Soils have played an important role in defining the various vadose zone hydrogeologic settings (see Section 3.2.3). Soils also form an important part of surficial mapping units (Section 3.1). Numerous buried soils may also lie in the subsurface. These buried soils, or paleosols, may serve as both potential barriers to infiltration through the vadose zone and as potential marker horizons that can be correlated between different drill holes.

Finally, geomorphology is the study of the configuration and evolution of the earth's surface. Many variables contribute to this evolution, such as climate, relief, base level (e.g., the lowest altitude to which erosion can lower the landscape), lithology, geologic structures, and human activity. A summary of the geomorphology and geomorphic provinces of SNL/KAFB is presented in Section 3.1.3.

The earth's surface defines the upper boundary of the hydrogeologic conceptual model. The relief of the landscape affects surface hydrology (for example, in the potential for runoff versus infiltration). In the Rift-Margin Ranges Province of eastern SNL/KAFB (Figure 3.1.3-1), rock-covered ridge lines and valleys form the headwaters for drainage basins that grade westward into the alluvial-fan complexes that dominate much of the Llano del Manzano and Llano de Sandia Provinces. Active arroyos on these alluvial-fan complexes are more prone to flooding and sediment transport than the topographically higher areas between the arroyos, otherwise know as interfluves. Because runoff concentrates surface water into arroyos and because arroyos have less soil development (a potential barrier to infiltration), arroyos may represent preferred locations for infiltration and (ultimately) recharge to the water table.

4.1.2 Hydrologic Processes

Hydrology is the science dealing with everything that happens to water from the time it reaches the earth's surface until it returns to the atmosphere or the ocean. The water may be temporarily stored where it falls or it may return to the atmosphere, become surface runoff, or percolate into the subsurface where it becomes groundwater. Figure 3.2-1 is a schematic diagram showing elements of the hydrologic system.

4.1.2.1 Interception

Precipitation may be in the form of rain, snow, frost, dew, or drip from fog. For the SNL/KAFB area, only rain and snow are considered to be significant precipitation. A portion of either rain or snow may be held by vegetation or organic litter on the soil surface, a process known as interception.

Most rain (and often a significant part of snow in vegetated areas) held in this manner is returned to the atmosphere by evaporation or sublimation (direct conversion from ice to water vapor). The relative significance of interception to the overall water balance is a function of the amount of vegetal canopy, soil litter, the magnitude and timing of the precipitation event, and (to a lesser degree) humidity. A number of literature sources provide estimates of the amount of water stored as interception in various environments (Haynes 1937, Lull 1964, Trimble 1959, Wisler and Brater 1959, Baldwin and Brooks 1936). An estimate of local interception rates would be about 0.03 in. at low elevations to about 0.1 in. at high elevations. Although these interception values are small, they are relatively large in comparison to the average amount of rain dropped by local rainfall events.

Snowfall captured by tree canopies is also subject to direct sublimation to the atmosphere. Virgin, eastern conifer forests are thought to have lost up to 25% of snowfall to interception, while the hardwoods that replaced the conifers may lose 10% of snowfall to interception (Baldwin and Brooks 1936).

4.1.2.2 Infiltration and surface runoff

Water reaching the soil surface either runs off as streamflow or infiltrates into the soil. With few exceptions, water infiltrates much more rapidly into a dry soil than a wet soil. The amount of water required to make a soil wet is substantial and will be discussed below. However, local soils are most frequently dry preceding rainfall events, and most water reaching the soils infiltrates. One clear indication that infiltration and interception are dominant over runoff is the amount of local streamflow. For example, the average annual measured runoff for the two USGS gages on Tijeras Arroyo between 1989 and 1994 was 0.03 area in. (i.e., 0.03 in. over their whole watershed area). These runoff measurements typically did not include the months of December through March, although flows are typically small during that season. The average measured runoff is approximately 0.3% of the depth of rainfall occurring at Albuquerque International Airport during this period.

4.1.2.3 Soil-water temporary storage

It is postulated above that almost all precipitation that falls in the area either is intercepted by vegetation or litter or infiltrates into the soil. For the present, assume that no interception occurs, and that all precipitation infiltrates into the soil. Figure 4.1.2-1 shows a generalized diagram of soil-water holding capacity. With the exception of a few rock outcrops, arroyo channels, and thin soil on mountain tops, most soils on KAFB are fine sandy loams, falling between sandy loam and loam in Figure 4.1.2-1. This indicates that after 24 hr of drainage following infiltration, these soils will typically hold slightly over 2 in. of water per ft of soil depth; this is the definition of the field capacity of a soil. On August 14 and 15, 1994, about 2 in. of rainfall fell during a 24-hr period at Albuquerque International Airport, and local broadcast stations announced this was the largest 24-hr rainfall event on record at that station. If the soil were completely dry preceding this rainfall, this rain could have been stored in the upper foot of a typical soil around SNL/KAFB, and if the soil were at 50% of field capacity, this rainfall could be held by the upper 2 ft of a typical SNL/KAFB soil. Normal average rainfall during summer months is less than 1.5 in./month (Figure 3.2.2).

4.1.2.4 Evapotranspiration

Evapotranspiration is the term used to describe the joint processes of evaporation and transpiration of water by plants. Either form of the transformation of liquid water to atmospheric vapor requires energy from sunlight. Evapotranspiration from a SNL/KAFB-area wet soil on a clear summer day is probably about 0.40 in./day (Wolford 1995); locally obtained estimates have been up to 0.34 in/day (Goetz and Shelton 1990). It seems reasonable to expect an inch of infiltrated rain to evapotranspire from SNL/KAFB-area soils within about four to five hot summer days, after which the soil's water-holding capacity will largely be restored to its prerainfall status.

Water within the upper foot of soil can be evaporated to the atmosphere directly without assistance from plants or other factors (Daubenmire 1959). Local plant roots extending more than 10 ft into deep soils along lower Tijeras Arroyo have been observed, suggesting that water may be drawn up from significant depths by local plants. In addition, the very thick vadose zone present under much of SNL/KAFB creates the potential for barometrically driven evaporation. For example, consider the effects of a change in barometric pressure from 1.0 in. of mercury (Hg) below the mean to 1.0 in. of Hg above the mean. At a mean barometric pressure of 25 in. of Hg, this is approximately equivalent to an 8% change in the mass of air occupying a given space. If that space is a 500-ft thick vadose zone, that change in pressure could effectively move external air into the uppermost 8%, or 40 ft, of the vadose zone. This air enters the soil at typically low ambient humidity, but when a subsequent lowering of pressure extracts that air from the soil, it will have a humidity of approximately 98% due to basic physical principles. At a temperature of 68°F, a soil porosity of 50%, and an ambient relative humidity of 50%, one such exchange of air would remove approximately 0.013 in. of water from the soil. While small compared to other forms of evaporation, this phenomena can extract water from greater depths than "normal" evapotranspiration. Where deep percolation is minimal, such effects may eliminate aquifer recharge altogether.

4.1.2.5 Soil-water potential

Except in the case of water ponding at the surface, the soil above the water table (i.e., in the vadose zone) is always in a state of unsaturation. Water in unsaturated soils is held to the soil particles and spaces between them by capillary forces (a function of surface tension of the water and the size of the opening) and by chemical attraction. These attractive forces are collectively known as matric potential (Hillel 1971). Matric potential can be described with several different units of measure, but the most easily understood is the height of a water column. Because the water held in unsaturated soil is under tension, matric potential is always negative or equal to a "hanging column" of water (such as water held in an upside-down glass with its lip under water).

Water always flows from higher to lower potentials. For example, the surface of a puddle of spilled water has a matric potential of 0; if a dry sponge (or a soil) with an adequately high negative matric potential is dipped into the puddle from above, the water can move upward into the sponge until the forces are in balance. When this balance of forces is reached, the matric potential (suction) at a distance 1 in. above the puddle surface will be equal to -1 in. of water. At a distance of 2 in., the matric potential will be -2 in. of water, and so on.

The elevation of a water column at a given location also constitutes a relative potential (i.e., water flows downhill). For the sponge in a puddle example, when forces are balanced at equilibrium, there is no more flow; by definition that indicates there is no difference in potential between the puddle and various points in the sponge. In the sponge equilibrium example, at 1 in. above the puddle surface, the -1 in. of matric potential plus the +1 in. of elevation potential sum to 0, the potential at the surface of the puddle. Carrying this analogy into the "saturated zone," at a depth of 1 in. below the puddle surface, the pressure potential is +1 in. of water, while the elevation potential is -1 in., which also equal 0, the potential at the surface of the puddle.

For a given amount of total water content, soils with finer textures (i.e., smaller particle sizes) will hold water at higher (negative) tensions. This can be seen clearly in Figure 4.1.2-1, where the field capacity of clay is nearly 4 in. of water per foot of soil, while the field capacity of sand is only about 1.2 in. Because water always flows from higher to lower potentials, if a clay with 2 in. of water per foot of soil is placed over a sand with 1.2 in. of water per foot of soil, water will not flow from the clay into the sand, but rather will flow upward from the sand into the clay. This is counterintuitive but true; i.e., placing a gravel layer under a fine-textured soil will not permit that soil to drain unless it is saturated, and then it will only drain to the point that water almost drips from the fine-textured soil above the gravel. An analogy is that a sponge will stop draining into open air while it is still very wet.

4.1.2.6 Flow in the unsaturated zone

The apparent velocity at which water flows through either an unsaturated or a saturated soil is proportional to the difference in total potential along the flow path and the hydraulic conductivity and is inversely proportional to the length of the flow path:

$$V = K(\Theta)\ \Delta h / \Delta L$$

where:

V = apparent (Darcy) velocity of flow,

$K(\Theta)$ = hydraulic conductivity at a given soil water content (unsaturated hydraulic conductivity),

Δh = change in potential between two points; this includes the gravitational (elevation) potential as well as the matric potential, and

ΔL = distance between the two points.

This is known as the Darcy equation. In unsaturated flow, the effects of changing water content on $K(\Theta)$ and soil matric potential are both large. For example, Figure 4.1.2-2 shows the unsaturated hydraulic conductivity curve for a coarse sand sample from the site of a neutron access tube in the main channel of Tijeras Arroyo. This curve shows that $K(\Theta)$ at a volumetric water content of 30% is about 100 times $K(\Theta)$ at a water content of 15%. Below 15% water content, the reduction in $K(\Theta)$ with declining water contents is larger. Draining by gravity alone at a water content of 8%, the apparent water velocity for this sample is about 1 in. per 245 days. In several finer-textured samples (described as fine sand to sand with gravel, materials much more coarse than the fine sandy loams said to cover most of SNL/KAFB) collected from depths up to 48 ft near the CWL, independent analysis indicated unsaturated hydraulic conductivity goes to 0 at water contents between 10.67 and 17.51% (Stephens 1989). The water content of these soils as found in the field averaged 4.07% with a high of 7.29%, suggesting they were much too dry for any unsaturated flow to occur. Finer-textured soils (e.g., those commonly present at the surface around SNL/KAFB, such as sandy loams) require higher water contents than do sandy, gravelly soils for any unsaturated flow to occur. The tension with which soil holds water (i.e., potential) also increases markedly with changing water content; the relative change in tension with a given change in water content is larger with coarser-textured soils. These tensions can get quite large under normal circumstances. Agriculturalists typically presume that agricultural plants will not die until 15 atmospheres of soil-water tension exist; this is equal in magnitude but opposite in sign to the pressure resulting from a 500-ft column of water, or about -220 lbs/in^2. Desert plants are expected to survive greater soil-water tensions than this.

4.1.2.7 Flow in the saturated zone

The water table is the top of the saturated zone and the bottom of the vadose (unsaturated) zone. In some cases, the saturated zone may be "trapped" between low permeability soil or rock units (called confining layers). In these cases, water will typically rise above the depth where it is first encountered when a well is drilled through the confining layer into the confined aquifer. The pressure present in a confined aquifer typically is provided by a recharge source located at a higher elevation. If the pressure within a confined aquifer is great enough, water may flow to the surface through a well (artesian well) or through natural conduits in the earth and result in a spring.

Sometimes the confining layer of a confined aquifer may uniformly leak; examples include thin clay layers or moderately permeable, clayey silt layers over an aquifer composed of coarser materials. Such leaky confining layers are referred to as aquitards, whereas a completely impermeable confining layer is an aquiclude. An impermeable or moderately permeable layer located above the regional aquifer may retard the downward migration of aquifer recharge water, resulting in a volume of water that is not directly connected to the regional water table. This is known as a perched aquifer. If the perching layer is very impermeable, very old water may remain perched without additional recharge for hundreds to thousands of years. No indication of this latter type of perching layer has been observed to date at SNL/KAFB, although carbonate cemented deposits, such as those evident along Arroyo del Coyote, may be this impermeable.

For porous media (e.g., cobbles, sand, silt, clay), water flow in the saturated zone follows the same Darcy equation discussed in Section 4.1.2.6. Under saturated conditions, $K(\Theta)$ becomes a constant known as saturated hydraulic conductivity. In addition, matric potential is 0 in saturated soils, so the total potential at a point is represented by either the top of the water table or the height to which water rises in a well placed at that point (hydraulic head, or simply "head"). If enough fractures are distributed throughout a bedrock aquifer, flow through the sum of those fractures also has been shown to follow the same equation as does flow in porous media; one difference is that porosity of a fractured rock aquifer is typically low, so that the true velocity of flow may be relatively high. As described here, the true velocity is the apparent velocity given in the Darcy equation (above) divided by the porosity (the volume of pore space divided by total volume of the material with the pore space). Porosity in porous media may be about 0.1 to 0.4; in fractured rock, porosity is the volume of the fracture divided by the volume of rock and therefore may be much smaller than 0.1.

Flow direction in a porous, homogeneous (uniform grain size) aquifer is always at right angles to lines of equal hydraulic head. However, vertical flows such as those that occur under a recharge mound are possible, in which case head decreases with depth in the mound. Anisotropies (nonuniform distribution of different material sizes) can also result in flow directions that are not at right angles to equal head lines. Anisotropies may be uniform, horizontal layers (such as clays under an ancient lake bed), in the vertical plane (such as along a fault where vertical movement has left a fine silt abutting a coarse sand at the same elevation), or at any other angle (e.g., buried alluvial fans). The effect on flow directions from these anisotropies could be calculated if their characteristics were all well known, but this is never the case several hundred feet beneath the land surface.

4.1.2.8 Estimated water budget for the KAFB area

The water budget is governed by the equation P = RO + R + ET (Precipitation = Runoff + Recharge + Evapotranspiration). For the KAFB area, precipitation (P) measurements during Water-Year (WY) 1995 were between 9.59 and 13.55 inches at measured sites within the low elevation portions of KAFB (see Section 3.2.1 and Table 3.2.1-1). Runoff (RO) for the KAFB area is approximated by the combined runoff from Arroyo del Coyote and Tijeras Arroyo with a drainage area of approximately 126 square miles. During WY-1995, measured RO from these drainages was approximately 13.65 million ft^3 or 0.06 area-inches (see Section 3.2.2 and Appendix A, Section A-3).

Our estimated recharge (R) to the aquifer is 5.6 million ft^3 (see Section 3.2.2.1 and Appendix A, Sections A7 and A8) and includes:

- Flow across line from School House Well to KAFB's southern boundary: 3 million ft^3/yr
- Tijeras Arroyo's channel bottom recharge on KAFB: 2.2 million ft^3/yr
- Arroyo del Coyote's channel bottom recharge: 400,000 ft^3/yr

This recharge estimate does not include recharge through the alluvial fans surrounding Manzano Base or mountaintop recharge in Arroyo del Coyote headwaters. Therefore our recharge estimate should be considered as a lower range estimate.

Though the drainage area for Tijeras Arroyo includes its off-base watershed, this drainage area and the recharge area are not greatly dissimilar in size. Therefore, assuming both surface runoff and recharge apply to the same areas, the combined RO and R total approximately 19.25 million ft^3 or about 0.08 area-inches.

Using the WY-1995 estimates for P, RO, and R, the calculated evapotranspiration (ET) is between 9.5 and 13.4 area-inches. This estimate indicates that in WY-1995 ET for the KAFB area was approximately 99 percent of the annual rainfall. This compares favorably to a previous estimate of ET of 95 percent of total annual rainfall (Thomson and Smith 1985).

4.1.2.9 Summary and application to Sandia National Laboratories/Kirtland Air Force Base

The hydrology of SNL/KAFB is controlled by a variety of interrelated factors, including climate, vegetation, soils, and geology. The physical processes governing water flow and the generalized physical influences on that flow have been described briefly above.

Because of the combined effect of low precipitation, soil-water storage, evaporation, and low unsaturated hydraulic conductivity in dry soils, no significant (if any) aquifer recharge is expected through the surface of those areas with reasonably deep soils and no concentrated water source (i.e., outside arroyo channels and lacking man-made sources such as septic tanks). The water source is too limited, the soil water storage capacity too great, unsaturated flow rates too low, and evaporative demand too large for such recharge.

Mountains and interarroyo areas east of the fault complex typically have shallow soils and fractured rock outcrops and may have above-average precipitation. The shallow soils and exposed rock should encourage above-average surface runoff. However, little surface runoff has been observed in the form of streamflow near the base of the mountains (although it undoubtedly sometimes occurs). This surface runoff must be going somewhere; one probable receptor is aquifer recharge. These areas support the densest vegetation in the complex, indicating that above-average evapotranspiration occurs here, which in turn requires a substantial storage of water within reach of the tree roots. It is suspected that much more water evaporates from these areas than is recharged.

Arroyos, especially those west of the fault complex, may be significant recharge sources where channel bottom materials are coarse-grained, where surface runoff persists long enough to move water to depths where it is not depleted by evapotranspiration, and where this water movement is not halted by underlying fine-grained layers.

4.2 HYDROGEOLOGIC CONCEPTUAL MODEL OF THE SANDIA NATIONAL LABORATORIES/KIRTLAND AIR FORCE BASE AREA

The hydrogeologic CM described in this section is a simplified descriptive working hypothesis of the interaction between the local SNL/KAFB geologic framework (Section 3.1) and the processes associated with the local hydrologic environment (Section 3.2). This CM is meant to be a reasonably realistic simplification of a very complex physical system and the processes in it (Bear 1979). The purpose of developing this CM is to provide an integrated description of the SNL/KAFB geologic setting and hydrologic characteristics and their associated uncertainties that affect the occurrence, movement, and interaction of surface and subsurface water. This CM will be used in the future to establish a quantitative understanding of potential pathways for transport of possible contaminants that may exist at SNL/KAFB ER sites.

4.2.1 Integrated Hydrogeologic Conceptual Model

The major portion of the SNL/KAFB area is located on a series of coalescent alluvial fans and piedmont alluvium east of the Rio Grande valley and west of the Sandia and Manzanita Mountains. SNL/KAFB is underlain by a wide range of geologic media including fractured rocks (granite, metasedimentary rocks, and limestone), sedimentary rocks (sandstone, siltstone, and shale), and poorly consolidated sediments. Hydrologically, this area is intermediate between the mountainous watershed/recharge region to the east, and the valley surface-water/groundwater discharge region to the west. In this position, the SNL/KAFB area is part of the historical hydrologic conduit, or pipeline, for both surface water and groundwater that flowed westward from the watershed/recharge regions in the mountains toward the Rio Grande valley discharge region.

Surface water flows through the SNL/KAFB area in arroyos, primarily Tijeras Arroyo and Arroyo del Coyote. These arroyos also function as local sources for groundwater recharge. Precipitation that falls on the interarroyo (interfluve) areas either runs off into the arroyos or evapotranspires.

Currently it is thought that essentially no groundwater recharge occurs in the interarroyo areas west of the foothills. Arroyos outside of the Tijeras Arroyo and Arroyo del Coyote drainages (i.e., those arroyos south of Arroyo del Coyote) almost never reach the Rio Grande. These arroyos widen into pseudo-playas from which the water evaporates. The western portions of these arroyos (e.g., near TA-III) are underlain with caliche, even where well channelized, indicating that they seldom flow and are not natural recharge sources. Near the mountains, flows in the southern arroyos may be more frequent and channel-bottom materials may be more permeable, thus allowing natural recharge to occur.

Groundwater flow includes both downward recharge flow in the exposed bedrock areas in the eastern part of the SNL/KAFB area and in the arroyo areas across the region and lateral (predominantly east to west) flow through the shallow alluvial and bedrock aquifers on the east, across the north-south fault complex that includes both bedrock and alluvial aquifers and through the thick Santa Fe Group aquifer on the west. At a local scale, groundwater flow (groundwater velocity and direction of flow) is controlled by the hydraulic characteristics of the aquifer media. Where bedrock is composed of igneous and metasedimentary rocks and limestone, fracture flow will predominate. Where fracture density and connectivity is sufficiently high, the fractured media will act hydraulically similar to porous media. However, irregular spacing of fractures and variability of fracture filling can result in preferential flow directions and in discrete high permeability flow paths. In sandstone/siltstone bedrock units and the unconsolidated alluvial/fluvial sediments, porous media flow will predominate. Porous media flow velocity is controlled by the hydraulic conductivity and porosity of the media and the magnitude of the hydraulic gradient. The direction of flow is controlled by the direction of the hydraulic gradient and the variation of hydraulic conductivity along the groundwater flow lines. The porous media aquifer units underlying SNL/KAFB are heterogeneous. This heterogeneity is characterized by hydraulic conductivities that range over approximately 5 orders of magnitude (0.001 to 147.1 ft/day), resulting in a large range in groundwater velocity. In addition, local variations in the geologic framework (bedding thickness, bedding connectivity, and depositional units with preferred orientations) contribute anisotropy to the aquifer. This anisotropy will exert local control on the direction of groundwater flow. The general direction of groundwater flow underlying SNL/KAFB is toward the west-northwest.

There are two complicating factors in the CM for groundwater flow beneath SNL/KAFB. The first factor is the impact of the north-south fault complex on the overall flow system. This fault complex bisects SNL/KAFB and has a very apparent impact on the area-wide flow system. This impact is seen in the large changes in water level as the faults are crossed from east to west.

The second important factor that has a significant impact on the groundwater system underlying SNL/KAFB area is the continual removal of large volumes of groundwater for the municipal water supply for the City of Albuquerque. This water supply pumping has changed the natural direction of groundwater flow beneath SNL/KAFB from predominantly west-southwest to west-northwest and has resulted in an annual decline in the local groundwater level ranging up to several feet per year. The closer an area is to the municipal well fields, the greater the impact pumping will have on groundwater flow.

4.2.2 Subareas of the Sandia National Laboratories/Kirtland Air Force Base Hydrogeologic Conceptual Model

As indicated in the above discussion, there is significant hydrogeologic complexity, both horizontally and vertically, over the SNL/KAFB area. While the entire hydrologic system on and beneath the SNL/KAFB area operates as a continuum, important hydrologic processes are strongly affected by the local hydrogeologic framework. Therefore, it is useful to subdivide the overall SNL/KAFB CM into subareas that exhibit relatively similar hydrogeologic characteristics.

The original, simplified description of the SNL/KAFB hydrogeologic environment subdivided the area into three hydrogeologic regions (see Section 3.2.4.2) (SNL/NM 1993). However, the work performed in the SNL/NM ER Project since 1992 indicates that this broad subdivision of the SNL/KAFB area does not adequately describe important local geologic and hydrologic characteristics. This section presents a more detailed breakdown of these three hydrogeologic regions and discusses the hydrogeologic characteristics typical for the individual subarea. Figure 4.2.2-1 shows the subareas within each hydrogeologic region.

4.2.2.1 Hydrogeologic Region 1

Hydrogeologic Region 1 (HR-1) occupies SNL/KAFB area west of the Sandia and Tijeras faults. HR-1 contains most of the SNL/NM sites that may have been impacted by past SNL/NM operations. Therefore, it is important that the hydrogeologic characteristics of the uppermost aquifer unit underlying this region be well defined so that ongoing and future ER Project site assessments can be accomplished in an efficient manner. Significant site characterization activities have taken place and are continuing in this region. Analyses of data gained through these site assessments have identified three subareas that exhibit important local hydrogeologic characteristics. These subareas include the area where the uppermost aquifer's water table is found in ancestral Rio Grande facies, the area where the water table is found in alluvial fan facies, and an area underlying Tijeras Arroyo where a shallow perched aquifer system exists (Figure 4.2.2-1).

4.2.2.1.1 Subarea A - Ancestral Rio Grande fluvial facies

Late in the history of the Albuquerque basin, before the present valley of the Rio Grande was cut (about 1 to 5 Ma), the river was located about 4 mi further east than at present (Lozinsky et al. 1991, Hawley and Haase 1992). The ancestral Rio Grande also flowed from north to south and deposited sediments that are now part of the upper Santa Fe Group. The ancestral Rio Grande Santa Fe Group fluvial facies typically have high (sand + gravel)/(silt + clay) ratios, are well sorted, exhibit relatively continuous and well-connected bedding with individual bed thicknesses greater than 5 ft with a preferred north-south orientation, and have moderate- to high-hydraulic conductivities. The City of Albuquerque municipal well fields north and west of KAFB draw water predominantly from this fluvial facies.

All available geophysical logs and sediment samples from SNL/NM and KAFB monitoring wells have been reviewed to identify wells having ancestral Rio Grande fluvial facies at the water table. For example, the water table is found within these fluvial facies in the ER Project monitoring wells PL-1 and MRN-1 (Plate II). A short distance east, the water table in monitoring wells in TA-III/V is found in Upper Santa Fe Group alluvial fan facies. The transition from predominantly fluvial facies to predominantly alluvial fan facies occurs between these locations. In this transition zone, ancestral Rio Grande facies intertongue with alluvial fan facies.

The Upper Santa Fe Group aquifer underlying this subarea is predominantly in ancestral Rio Grande facies and is semiconfined with relatively high hydraulic conductivities ranging from approximately 12 to 147 ft/day. The upper 100 ft of this aquifer does not exhibit a significant vertical gradient. The gradient is 0.001 to 0.008 ft/ft (downward) at the MRN and PL monitoring well locations respectively. The predominant preferred flow paths in this facies will be north-south. Because the municipal well fields adjacent to the SNL/KAFB area draw water primarily from these facies, this subarea is more affected by water supply pumping.

4.2.2.1.2 Subarea B - Alluvial fan facies

The other major facies of the Upper Santa Fe Group were deposited as alluvial fans that transported sediment eroded from the mountains on the east. These alluvial fan facies interfinger with the fluvial (river-transported) sediments of the ancestral Rio Grande.

The alluvial fan facies typically have a moderate to high (sand + gravel)/(silt + clay) ratio, are poorly sorted, exhibit lenticular bedding that is moderately to well connected with individual bed thicknesses between 1 and 5 ft with a preferred east-west orientation, and have moderate- to low-hydraulic conductivities. These Upper Santa Fe Group alluvial fan facies extend eastward from their boundary with the ancestral Rio Grande facies to a north-south line that is coincident with the Sandia fault and the southern extension of the Tijeras fault.

The uppermost water-bearing unit in the alluvial fan facies south of Tijeras Arroyo consists of up to 50 ft of silty clay. Below this fine-grained unit is an interval of approximately 85 ft that includes several sand layers, each approximately 10 to 15 ft thick. Most monitoring wells are completed in the upper fine-grained unit that generally has a low hydraulic conductivity (0.001 to 0.039 ft/day from aquifer pumping tests at the MWL and the CWL), acts semiconfined, and has a downward vertical gradient resulting in downward vertical flow in the upper, fine-grained interval.

At several locations in the TA-III/V area, there are monitoring wells completed in one of the underlying sand units. The hydraulic conductivity in these intervals is higher (21.6 to 27.4 ft/day from aquifer pumping tests at the CWL), while the hydraulic head is lower than the head in the overlying fine-grained unit. At the CWL, monitoring wells completed in a deeper sand interval and separated by a horizontal distance of up to approximately 300 ft responded together during an aquifer pumping test (MW-2B [lower], MW-5 [lower], and MW-6 [lower]). This indicates that the sand intervals are relatively continuous at the scale of the CWL. It is possible that the sand intervals may be connected to the fluvial facies to the west, which could result in water supply pumping preferentially removing water from these underlying more, permeable beds. This hypothesis could explain the lower hydraulic head in these sand intervals.

4.2.2.1.3 Subarea C - Area of shallow groundwater in the vicinity of Tijeras Arroyo

A 1993 assessment of shallow groundwater underlying the Tijeras Arroyo Golf Course (TAGC) and TA-II concluded that shallow groundwater elevations existed in the vicinity of Tijeras Arroyo above its confluence with Arroyo del Coyote (SNL/NM 1994). This shallow groundwater is found within the alluvial fan facies of the Upper Santa Fe Group.

In 1994, several SNL/NM ER Project activities provided new information related to the assessment of high groundwater elevation in the vicinity of Tijeras Arroyo. These activities identified shallow groundwater at two new locations (monitoring wells TJA-2 and TA2-W-01) and confirmed that a large area between TA-II and the TAGC is underlain by relatively shallow groundwater (SNL/NM 1995). In 1995, shallow groundwater was found in the ER Project monitoring well WYO-2 (see Appendix C), which pushed the apparent limit of this system approximately 0.5 mi west of TA-II.

There are now eight monitoring wells completed near the top of this shallow groundwater system. Figure 3.2.4-4 is the potentiometric surface map for this shallow system. This map shows that the upper surface of this system slopes toward the southeast. An aquifer pumping test was performed in monitoring well TJA-2, which is completed in a sand interval near the top of this shallow system. The data from this test indicate that the hydraulic conductivity for a shallow aquifer at this location ranges between 17 and 50 ft/day (Appendix D.5.2). Analysis of data from slug tests in other monitoring wells (KAFB-0310, -0602, -0608, -0609, and -0610) completed in this shallow system gives hydraulic conductivity values ranging from 0.21 to 34.90 ft/day (USGS 1993).

The current conceptual model for the shallow groundwater in this area is a system of multiple perched aquifer intervals that extend up to 200 ft above the regional water table. During the drilling of the TA2-NW1-595 monitoring well, at least five perched intervals were identified (SNL/NM 1994). This perched system is related to recharge, primarily from Tijeras Arroyo, much of which may enter the ground upstream of SNL/KAFB. Additional localized, minor sources of recharge in this area could include waste-water discharges to ditches and leach fields and leakage from irrigation and surface impoundments, e.g., the TAGC. The uppermost surface for this system is found near the WYO-1 monitoring well. The water surface may not be continuous between WYO-1 and TAGC, but if it is, it appears to be lowest near the TAGC. The northern limit of the system is north of the TA2-NW1-325 monitoring well and south of the PGS-1 monitoring well location (horizontal distance of approximately 4900 ft). The southern limit is currently unknown, but it may extend to the Tijeras Arroyo/Arroyo del Coyote confluence. The thickness of individual perched intervals is currently unknown, but it may range from less than 5 ft to more than 20 ft.

4.2.2.2 Hydrogeologic Region 2

Hydrogeologic Region 2 (HR-2) straddles the Tijeras/Sandia/Hubbell Springs fault complex. The surface geology in this region includes a thin cover of piedmont alluvium and bedrock outcrops. The subsurface geology includes Santa Fe Group sediments to the south, an indurated Tertiary conglomerate near the center, and Paleozoic/Precambrian bedrock to the north. The overall hydrogeologic CM in this region is complicated by this variation in geologic media and the faulting. To adequately characterize its stratigraphic complexity, HR-2 is divided into three subareas that exhibit important local hydrogeologic characteristics (Figure 4.2.2-1). The other important local element in the overall CM are the faults. A separate discussion on the impact of faulting on groundwater flow addresses this important CM element.

4.2.2.2.1 Subarea D - Manzano block

The Manzano Base block is a wedge-shaped area bracketed by the Sandia fault on the west and the Tijeras fault on the east. The surficial geology on this block includes a very thin cover of predominantly very coarse piedmont alluvium and large outcrops of weathered granite (Four Hills area) without any significant vegetation. The coarse and fractured nature of the surficial geology and the lack of vegetation on the granite outcrops suggest that this block could be an effective recharge area for local precipitation and runoff.

As part of the KAFB underground storage tank (UST) assessment project, one relatively deep monitoring well of about 130 ft and several shallow monitoring wells of about 60 ft have been installed near the eastern boundary of this block. Analysis of the deep monitoring well showed weathered granite to a depth of about 90 ft and then fresh granite for another 40 to 50 ft. This monitoring well did not encounter the regional aquifer. However, a shallow perched aquifer was found at a depth of about 55 ft (Holmes 1995). KAFB is currently investigating this perched aquifer and will report on this investigation in 1996. Near the northern end of this block, there is an old homestead water well known as the Yates well. The well depth is estimated to be about 52 ft with a depth to water of about 20 ft (estimated water level elevation is 6060 ft msl). The surface geology at the well is weathered granite. It is possible that the well taps a perched aquifer such as the one encountered in the KAFB UST investigation.

The presence of perched aquifers in the weathered granite at two locations supports the hypothesis that this block could be an effective recharge area for local precipitation and runoff. Although there are no monitoring wells in the Manzano block that are completed in the deeper regional aquifer, this aquifer will be found in fractured rock. It is assumed that the hydraulic gradient will be toward the west. One aquifer pumping test was performed in a fractured granite well further east in the canyons and foothills region (monitoring well TSA-1). The hydraulic conductivity for the fractured granite at the TSA-1 location was estimated to range from 1.7 to 2.2 ft/day (SNL/NM 1994).

4.2.2.2.2 Subarea E - Travertine block

The Travertine block is located in south-central KAFB. This block is bounded by the Tijeras fault on the west and the cross-over fault that connects the Tijeras fault to the Hubbell Springs fault on the south. The eastern boundary of the block follows the extension of the Hubbell Springs fault north from the cross-over fault. The northern boundary of the block is an east-west line extending east from near the intersection of the Sandia and Tijeras faults. The surficial geology of this block includes a thin cover of piedmont alluvium and rolling hills of a weathered Tertiary conglomerate.

The SNL ER project has installed one monitoring well in this block at the STW location (see Appendix C). During drilling at this location, several intervals of lost circulation were encountered in the Tertiary conglomerate down to a total depth of 521 ft. These intervals of lost circulation indicate that there are highly transmissive features in the Tertiary conglomerate that may be either poorly cemented conglomerate beds or fracture zones. The depth to water in the STW-1 monitoring well was 154.7 ft on November 3, 1995 (elevation 5378.2 ft msl). It is assumed that the hydraulic gradient will be toward the west.

An unnamed arroyo passes through this area along its path from the Mount Washington area to near the southern boundary of TA-III, where it dissipates within TA-III. This arroyo flows very infrequently and is not believed to be a source of aquifer recharge. An abandoned, breached dam exists between two hills near the northwest corner of this block, indicating someone once thought otherwise. A stream gage was installed on this arroyo just inside TA-III in June 1995 (about 3000 ft west of this block). This gage recorded two rises in water level during 1995. Close examination showed that the water level rise was due to ponding caused by a plugged channel just downstream of the gage. No flow had occurred in the channel upstream of TA-III, and the ponding was caused by road-surface runoff in the immediate vicinity. Runoff in this channel was not believed to be any more significant during WY94, although an automatic water sampler located at this site was triggered and collected a sample during WY94. Exploratory holes dug in the arroyo bottom about 500 yd upstream of the TA-III boundary fence (halfway between TA-III and this hydrogeologic block) found extensive and heavy caliche deposits within about 10 in. of the channel bottom. While these deposits are probably not impermeable, they suggest that no recharge occurs here. Any significant vertical water movement through the soils containing these deposits would have either prevented their formation or leached them away.

4.2.2.2.3 Subarea F - Thunder Range block

The Thunder Range block is bracketed by the Tijeras fault on the west and the Hubbell Springs fault on the east. The northern boundary of the block is at the cross-over fault that connects the Tijeras and Hubbell Springs faults. The southern boundary is arbitrarily set at the boundary line between KAFB and Isleta Pueblo. The block is assumed to extend southward some unknown distance onto the Isleta Indian Reservation.

The surficial geology of this block is a thin cover of piedmont alluvium. The subsurface geology is composed of the alluvial fan facies of the Upper Santa Fe Group underlain on the east by a Lower Tertiary sandstone/siltstone unit (SNL/NM 1995).

Monitoring wells are found at four locations within this block. The water levels in these wells are 300 to 400 ft higher than water levels at the MWL and CWL, approximately 3 and 2 mi to the northwest, respectively. The horizontal hydraulic gradient in this block is toward the west-northwest. This hydraulic gradient ranges from 0.002 ft/ft between the SFR-3 and SFR-2 monitoring well locations and 0.010 ft/ft between the SFR-2 and SFR-1 monitoring well locations.

Two water-bearing intervals within the Santa Fe Group have been identified (SNL/NM 1995) (Appendix D). The uppermost interval is continuous across the area. The lower interval was identified in two wells (SFR-1D and TRE-1) near the western boundary of the block (Tijeras fault). The preliminary interpretation is that the upper and lower water-bearing intervals are part of a single Santa Fe Group hydrogeologic unit that is localized in the Thunder Range block. There is a downward vertical gradient between these intervals between 0.08 (TRE-1/TRE-2) to 0.25 ft/ft (SFR-1S/SFR-1D) as measured from the middle of the screen intervals. One aquifer pumping test performed in the SFR-3P monitoring well completed in the Santa Fe Group yielded an estimate for the hydraulic conductivity of 10.34 ft/day (SNL/NM 1995).

At the SFR-3 location in the southeast corner of this block, one monitoring well (SFR-3T) was drilled completely through the Santa Fe Group and completed in the underlying Lower Tertiary bedrock. The water level elevation for this bedrock interval is approximately 70 ft higher than the water level in the overlying Santa Fe Group aquifer. This indicates that there is an upward vertical hydraulic gradient from the bedrock into the Santa Fe Group of approximately 0.13 ft/ft. In addition, one aquifer pumping test accomplished in the SFR-3T monitoring well completed in the Lower Tertiary sandstone/siltstone bedrock yielded an estimate for the hydraulic conductivity of 0.0032 ft/day (SNL/NM 1995).

The uppermost aquifer in this block is in the alluvial fan facies of the Upper Santa Fe Group. Groundwater flows into this block from the shallow alluvial aquifer and confined bedrock aquifers to the east across the low-permeability Hubbell Springs fault. Within the Thunder Range block, the Santa Fe Group aquifer is both unconfined and semiconfined and flows toward the west-northwest. Gradients are shown on the potentiometric surface map (Plate IV).

4.2.2.2.4 Role of the fault complex in the conceptual model

One issue that has been considered is whether the faults on SNL/KAFB are low-permeability or high-permeability features. Available data do not strongly support either of these options. Haneberg (1995) reported on modeling results that he suggested were indicative that these faults are low-permeability features. However, the generic aquifer system presented in Haneberg (1995) considered confined aquifers with the head differences across these faults being piezometric, rather than elevational (free surface) heads. While the SNL/KAFB-area aquifers do behave as though they are confined, most often free water is present in the aquifer materials at the height of the piezometric surface, suggesting that the aquifers are only partially confined. East of the faults, some areas have combinations of confined aquifers capped by shallow but highly transmissive unconfined aquifers. The most notable difference between cross-fault aquifers here and those modeled by Haneberg (1995) is probably the very large offset (i.e., 300 ft) in the elevations of the saturated surfaces across local faults. It is difficult to believe that confined conditions exist in flows across the faults themselves, given the 300 ft difference in water surface elevations from eastern to western aquifers. Even so, knowledge of area hydrogeology can be interpreted to suggest faults are either high- or low-permeability features.

First, consider the effects on head gradients caused by differences between transmissivity in the aquifers east and west of the fault when the fault is ignored. Assume the transmissivity of the aquifer east of the fault is 20% of the transmissivity of the aquifer west of the fault and that flow is from east to west across the fault. Because the transmissivity in the east aquifer is lower, the gradients in that aquifer must be 5 times larger than the gradients in the western aquifer to transmit water at the same rate. Generally, this is approximately the difference between the gradients that exists in these aquifers (Plate IV).

Second, assume that the fault is a low-permeability feature, that the upper surface of the eastern aquifer is not confined, and that all recharge to the aquifer is from mountain tops and mountain fronts to the east. At points far to the east of the fault, the gradient and aquifer thickness will be the same as if the fault were not present. Near the fault, though, the fault itself becomes the limiting factor to flow. If the flow across the fault is unconfined, low heads on the western side of the fault cannot drive the flow; i.e., low heads cannot create tension equal to 300 ft of water. In effect, the fault acts like a subsurface dam. The depth of water behind the fault will increase until the increased depth and pressure from the supply side (east) increase, until the flow through the fault matches that coming from the east. Under this scenario, groundwater head gradients should decrease and aquifer thicknesses increase in a westerly direction as the fault is approached from the east. Increased heads east of the fault caused by the low-permeability fault could be responsible for Hubbell Springs. Arguably, flatter gradients are present in the area just north of wells SFR-2 and SFR-3, where the 5300-ft and 5250-ft contours that have been mapped are not supported by any hard data.

Finally, assume the fault is a high-permeability feature or is otherwise hydrologically "transparent" to the flows and the flows are unconfined across the fault. In this case, water moves to and from the fault similarly to the first case described above (no fault), except very close to the fault itself. As the water approaches the fault, the lowered resistance to flow caused by the higher permeability fault (or the higher permeability material on the west side of a "transparent" fault) causes the water surface to draw down as would water flowing over a dam. The increased gradients in the water surface are balanced by the thinner aquifer to maintain steady-state flow rates equal to those in the aquifer to the east. In effect, the water "seeps" across the fault until it reenters the western aquifer, where it flows the same as in other cases described above (i.e., same gradient and depth). This scenario does not require totally unconfined eastern aquifers; any number of confined aquifers could approach the fault and join the "seeping," unconfined waters across the fault. The length of the drawdown curve to the east caused by the "free surface" (though buried) outlet at the fault could be very short, particularly in the case of multiple thin confined aquifers underlying a thin unconfined aquifer. Therefore, the hydraulic gradient approaching the fault from the east may not show significant deviation from the "no fault case" of constant gradients unless measured very near (e.g., perhaps less than 200 ft) the fault. Arguably, the hydraulic gradients approaching the fault appear to be approximately constant (Plate IV) and thus support this model.

4.2.2.3 Hydrogeologic Region 3

Hydrogeologic Region 3 (HR-3) lies to the east of the Tijeras/Hubbell Springs fault complex and includes a piedmont plain between the fault complex and the mountain-front Coyote fault and the piedmont foothills/Manzanita Mountain area east of the Coyote fault (Figure 4.2.2-1). The surface geology in this region includes a thin cover of alluvium on the piedmont and bedrock outcrops in the foothills and mountains. The subsurface geology includes shallow alluvium and Paleozoic/Precambrian bedrock. The overall hydrogeologic CM in this region is complicated by this variation in geologic media. To adequately characterize its stratigraphic complexity, HR-3 is divided into two subareas that exhibit important local hydrogeologic characteristics.

4.2.2.3.1 Subarea G - Hubbell Bench area

The region east of the Tijeras-Hubbell Springs fault zones and south of Arroyo del Coyote is characterized by a thin cover of alluvium laying over shallow bedrock. The alluvium consists of unconsolidated sand and gravel underlain by much older consolidated bedrock. The thickest alluvium occurs in the southwestern part of the area in the vicinity of the ITRI facility (SNL/NM 1995) where it fills a paleodrainage incised on the bedrock surface. The top of the saturated zone occurs within the alluvium in some areas and within the bedrock in others.

Where the top of the saturated zone is within the alluvial fill of paleochannels at ITRI, the paleochannels control flow directions (Attachment 1, Figure 4.0.1). It is possible that a buried paleochannel extending northeast from ITRI may connect subsurface flows from the Arroyo del Coyote/Coyote Springs area to flows from EOD Hill and ITRI (Attachment 1, Figure 4.0.1).

Paleotopographic data used to generate the paleotopographic model are only available in the area where bedrock exists at shallow depths. That situation exists only east of the "fault complex." The model is best demonstrated in the ITRI area, where there are more than 30 closely spaced wells providing subsurface control points. Northwest, north, and northeast of ITRI, the model can be applied using several rock outcrops, refraction seismic data, but only six wells; these data points result in the mapping of other, less clearly defined paleochannels. We incorporated the flow effects from these channels, in connection with a piezometric surface map, into a flow-directional model (see Section 3.2.4.3.3 and Figure 3.2.4-3).

The paleodrainage model is not applicable west of the fault complex because there are no wells known to encounter bedrock.

Plate III shows the geologic units that contain the uppermost aquifer. When the uppermost aquifer is found in alluvium, it is unconfined to semiconfined and generally has a high hydraulic conductivity. The analysis of data from aquifer slug tests and aquifer pumping tests performed in the alluvium at the ITRI facility has identified hydraulic conductivities between approximately 6.24 to 152.2 ft/day (PRC 1990 and 1993). The groundwater in the alluvial aquifers is thought to be provided by horizontal flow from the adjacent bedrock aquifer units. Some minor recharge to the saturated alluvium may take place under surface-water impoundments (i.e., the historical ITRI sewage lagoons and Lake Christian) and septic systems/drainfields.

When the uppermost aquifer is found in bedrock units, it will be a confined aquifer. The hydraulic conductivity and general flow characteristics will depend on the rock type. At the TRN-1 location, the monitoring well is completed in Permian Abo Formation sandstone and siltstone. The analysis of data from an aquifer pumping test in this monitoring well yielded an estimated hydraulic conductivity of 0.16 ft/day (Attachment 4). Approximately 1000 ft east south-east from the TRN-1 monitoring well, two monitoring wells (TRS-1 and TRS-2) were drilled into the Madera Formation. This formation includes fractured and vuggy limestone intervals. In 1995, the TRS-1 borehole was completed with two monitoring intervals and shows that there is an upward vertical gradient in the Madera limestone of approximately 0.11 ft/ft. No aquifer testing has taken place in these wells. However, from indications during drilling and borehole video logs (SNL/NM 1995), the hydraulic conductivity of the Madera Formation at this location is expected to be very high. Plate IV is the potentiometric surface map of the uppermost regional aquifer.

Two infiltration measurements were taken during 1993 along arroyos in the Mt. Washington area, both of which showed infiltration rates of about 30 ft/day (Appendix A, Table A-5). Generally, arroyo-bottom materials near the mountains are coarse textured and shallow to bedrock. Some cemented, impermeable fractures in inter-arroyo bedrock outcrops were observed along the southern boundary of KAFB. However, whether fractures beneath these arroyos are typically open or closed is not known. If they are open, flow in these arroyos may be the principal source of aquifer recharge for the Hubbell Bench.

The basic shape of the surface watersheds in this block is different from that of Arroyo del Coyote. Specifically, the Arroyo del Coyote watershed has a light bulb shape, while watersheds in the Hubbell Bench area are long and rectangular. As a result, the ratio of the length of the main arroyo channel per unit area or watershed is larger here than in Arroyo del Coyote. This results in inherently less runoff available per foot of main channel length, which may partially explain why most arroyos in this region disappear before leaving SNL/KAFB. Flow measurements made in the Arroyo del Coyote basin show maximum runoff to be about 0.014 area in. (i.e., 0.014 in. over the entire watershed area) see Section 4.2.2.3.2 and Appendix A). Because the Hubbell Bench channels appear to flow less frequently, potential recharge through the arroyo bottoms (i.e., streamflow) here is probably less than 0.015 area in.; the educated guess would be 0.005 area in. of potential recharge through arroyos. For the portion of this basin from EOD Hill east to the Manzano Lookout Tower and south to the KAFB boundary, this is equal to about 100,000 ft^3/yr. In contrast, the best (to date) estimate of total flow in the subsurface in this basin is about 3 million ft^3/yr (Appendix A, Section A.7). It is suggested that mountain-top recharge (including arroyo flow immediately adjacent to the mountains) comprises over 90% of aquifer recharge in this basin.

West of the line between EOD Hill and the southern KAFB boundary, natural recharge is expected to be near zero. The most likely source of recharge, the arroyo, was found to be underlain with caliche just west of this area, about 1500 ft east of TA-III (Section 4.2.2.2.2).

4.2.2.3.2 Subarea H - Canyons and foothills area

The canyons and foothills area is located east of the Coyote mountain-front fault. The surface geology in this region includes alluvium in canyon areas, especially Lurance Canyon downstream into Arroyo del Coyote, and exposed bedrock, primarily Precambrian granite and metasedimentary rocks, with some upland areas of Paleozoic Madera Formation limestone and Sandia Formation sandstone.

Information gained from streamflow gaging, seismic surveys, and drilling done in Lurance Canyon in 1994 suggests that there is no significant alluvial aquifer along the stream channels upstream of Coyote Springs (SNL/NM 1995). However, the potential for water infiltrating into the canyon alluvium and becoming temporarily perched along the alluvium-bedrock contact exists. To evaluate this potential, the SNL/NM ER Project is developing a field program to install piezometers across this contact in the vicinity of the Burn Site in upper Lurance Canyon.

Recharge through the alluvium is considered minimal; if any recharge occurs, it is diverted into fracture flow in bedrock aquifers. Groundwater is present in fractured rock underlying this area. Wells in the canyons and foothills produce groundwater from confined fractured aquifer systems (e.g., TSA-1, Burn Site, Optical Range, and High Energy Research Tests Facility [HERTF] wells) (SNL/NM 1994). For example, the Burn Site well gets its water from fractures in schists and granite at depths of approximately 222 to 350 ft bgs, with the water rising within the well to 68 ft bgs (SNL/NM 1995).

This area is characterized by recharge to the area-wide groundwater system through fractured bedrock on the mountain tops and canyon side slopes. Groundwater flow is primarily in bedrock units with the horizontal component of flow going from east to west. There is some upward vertical flow where vertical fractures extend to the surface (i.e., springs). In addition, there is probably some minor subsurface flow within the canyon alluvium, either in response to precipitation or from upward leakage from the bedrock aquifer.

Fracture patterns (direction and orientation) and fracture characteristics (density, aperture, and fracture filling) within the bedrock will impact groundwater flow. As part of the Site-Wide project, a limited fracture characterization study was accomplished (see Attachment 1, Section 2.2.4). The conclusions of this study yielded little definitive information on a predominant orientation or the nature of fracture characteristics in Subarea H. However, it should be understood that fractures will play a significant role in groundwater flow in this area and that all site-specific investigations should factor this into investigation planning and hydrogeologic data analysis.

Geochemical studies indicate that water from Coyote Springs and the EOD Hill monitoring well may share a common source, probably very deep groundwater. Although alluvial aquifers to the east of Coyote Springs are not known, some alluvial water has been discovered in boreholes along Arroyo del Coyote above G-Spring, and G-Spring itself may be a discharge site for alluvial water (Plate I). Water discharged at Coyote Springs that has not evapotranspired enters the arroyo where it may either become alluvial groundwater or reenter the bedrock.

Measured surface runoff in area channels is small; the largest annual flow measured during WY94 and WY95 is equal to about 0.014 area in. of runoff (i.e., 0.014 in. over the entire watershed area; Appendix A, Table A-2). This indicates that the potential for aquifer recharge through arroyos in these canyons is very limited. However, the cell size of intense rainstorms is small, and the stream gages installed measure watersheds of 6 mi^2 and larger. The disposition of rainfall on mountain tops, side slopes, and at the base of these mountains in the vicinity of intense storms is unknown. The majority of recharge that does occur in these areas is believed to occur either through fractures in rocks on the tops and side slopes of the mountains or through infiltration into coarse-textured alluvium at the bases of these mountains (mountain-front recharge). Mountain-front recharge as used here includes infiltration through arroyos immediately adjacent to the mountains.

4.3 MAJOR CONCEPTUAL MODEL UNCERTAINTIES

The SNL/KAFB-area hydrogeology system is highly complex. This complexity can never be fully described such that there are no uncertainties remaining. The best that can be done is to develop a CM that is a realistic simplification of this complex hydrogeologic system. This CM provides the SNL/NM ER Project with the basis for the development of quantitative tools (analytical and numerical models) needed to assess potential pathways for groundwater transport of possible contaminants at SNL/KAFB ER sites.

The necessary level of quantitative understanding of the hydrogeology system at any site will depend on the site-specific characterization requirements. For example, at a site in HR-1 with suspected surface contamination, it may be sufficient to know that the depth to groundwater is generally greater than 400 ft. At another site that discharged process water to the subsurface over a 20-yr period, a much more detailed description of the site-specific groundwater hydrogeologic framework may be required. In both cases, the CM provides necessary information. In the first example, the uncertainties in the existing model of the site-specific groundwater system are not significant and no additional hydrogeologic characterization will likely be required. In the second example, some additional site-specific groundwater characterization may be needed. However, the existing CM will provide a valuable starting point and will help guide any further characterization actions to efficiently address the site-specific uncertainties.

In addition to site-specific uncertainties, there are uncertainties related to interpretations embodied in the CM. For example, the SNL/NM CM interprets the existing hydraulic head field in the vicinity of the faults to indicate that the faults are low transmissivity hydrogeologic features. While there are uncertainties in this interpretation, these uncertainties may not impact quantitative assessments of groundwater contaminant transport from some, if not all, SNL/NM ER sites. However, if this interpretation is a critical element in an ER site assessment, then the uncertainties related to it will need to be addressed in that ER site assessment.

From the above discussion it is apparent that there will always be uncertainties in the CM of the hydrogeology. However, only those uncertainties that directly impact the ability to accomplish a necessary site-specific assessment may need to be addressed. After these site-specific and/or interpretive uncertainties are reduced so that the necessary level of assessment is accomplished, any new information that reduces or eliminates specific uncertainties can be integrated into the CM.

At this stage in the development of the SNL/KAFB CM, significant uncertainties are known to exist in several hydrogeologic subareas. In addition, the acquisition of additional data related to aquifer parameters, groundwater geochemistry, and subsurface geology will improve the ability to quantitatively assess groundwater flow paths. Tables 4.3-1, 4.3-2, and 4.3-3 provide a summary listing of significant uncertainties in the CM and identify additional useful data. These tables are organized based on hydrogeologic regions and subareas within these regions to be of assistance to an ER site assessment.

Table 4.3-1. Summary of Conceptual Model Uncertainties and Identification of Additional Data That Would Be Useful for Quantitative Assessments in Hydrogeologic Region 1

	Significant Conceptual Model Uncertainties	Useful Additional Data *
Subarea A - Ancestral Rio Grande fluvial facies	Geometry of intertonguing with overlying alluvial fan facies	Subsurface geologic profile from top of regional aquifer into the underlying Middle Santa Fe Group
Subarea B - Alluvial fan facies	Geometry of intertonguing with underlying fluvial facies	Additional multilevel monitoring wells to assess vertical flow in upper fine-grained unit
Subarea C - Area of shallow groundwater in the vicinity of Tijeras Arroyo	Geometry of shallow aquifer system (horizontal extent, lateral connectivity, horizontal hydraulic gradient) Vertical saturation profile (number of perched intervals, vertical connectivity) Recharge source and path	Groundwater geochemical characteristics (major anions/cations, isotopes for age dating, comparisons to regional groundwater geochemistry) Contaminant transport characteristics (dispersivity, diffusion coefficients, distribution coefficients)

* The SWHC Project has no plans to collect additional data or to reduce the uncertainties identified in this table.

Table 4.3-2. Summary of Conceptual Model Uncertainties and Identification of Additional Data That Would Be Useful for Quantitative Assessments in Hydrogeologic Region 2

	Significant Conceptual Model Uncertainties	Useful Additional Data *
Subarea D - Manzano block	Impact on flow system boundary conditions	Aquifer parameters Groundwater geochemistry Depth to regional aquifer Hydraulic gradient of regional aquifer across block
Subarea E - Travertine block	Aquifer parameters	Thickness of Tertiary conglomerate Groundwater geochemistry
Subarea F - Thunder Range block	Hydraulic gradients adjacent to Tijeras fault	Thickness of Santa Fe Group just east of Tijeras fault
Role of fault complex in the groundwater flow system	Nature of groundwater flow across fault	Additional field-based studies to measure hydraulic gradients across faults and along faults Surface geophysics to define fault geometries Groundwater geochemistry

* The SWHC Project has no plans to collect additional data or to reduce the uncertainties identified in this table.

Table 4.3-3. Summary of Conceptual Model Uncertainties and Identification of Additional Data That Would Be Useful for Quantitative Assessments in Hydrogeologic Region 3

	Significant Conceptual Model Uncertainties	Useful Additional Data *
Subarea G - South piedmont area	Impact of the Coyote fault on the groundwater flow system Hydraulic connection between canyon alluvium and enclosing bedrock	Groundwater geochemistry
Subarea H - Canyons and foothills area	Hydraulic connection between canyon alluvium and enclosing bedrock Extent of alluvial aquifer	Fracture studies Groundwater geochemistry Additional bedrock monitoring wells Piezometers across the alluvium-bedrock contact

* The SWHC Project has no plans to collect additional data or to reduce the uncertainties identified in this table.

The objective of the SWHC Project was to determine the generalized, overall regional framework of geology, hydrology, and hydrogeology which together determine the regional flow patterns of water and, by extension, flow patterns of contaminants that may be transported by that water. This report meets that objective and completes the SWHC Project. No additional field work or data analysis, including those described as providing "useful additional data" in Tables 4.3-1 through 4.3-3, has been planned for the SWHC Project. SNL/NM task leaders and regulators for individual sites may make determinations on the need to collect any "useful additional data" which are deemed necessary to complete a site-specific evaluation.

4.4 REFERENCES

Baldwin, H. I., and C. F. Brooks, 1936. Forests and Floods in New Hampshire. New England Region Planning Commission Pub. 47. Referenced from Lull (1964).

Bates, R. L., and J. A. Jackson, editors, 1987. Glossary of Geology, Third Edition. Alexandria, Virginia: American Geological Institute.

Bear, J., 1979. Hydraulics of Groundwater. New York: McGraw Hill.

Birkeland, P. W., 1984. Soils and Geomorphology. New York: Oxford University Press.

Brownlow, A. H., 1979. Geochemistry. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Catt, J. A., 1988. Quaternary Geology for Scientists and Engineers. Chichester, West Sussex, England: Ellis Horwood Limited.

Daubenmire, R. F., 1959. Plants and Environment. Second Edition, New York: Wiley. Referenced from Lull (1964).

Goetz, C. L., and S. G. Shelton, 1990. Infiltration and evapotranspiration within the Albuquerque, New Mexico, Area with a section on historical water-resource trends during the 1954-80's period of urban growth. U.S. Geological Survey, Water-Resources Investigations report 90-4055, Albuquerque, NM. 96 p.

Hawley, J. W., and C. S. Haase (eds.), 1992. Hydrogeologic Framework of the Northern Albuquerque Basin, New Mexico Bureau of Mines and Mineral Resources Open-File Report 387.

Haynes, J. L., 1937. Interception of Rainfall by Vegetative Canopy. USDA Soil Conservation Service, American Society of Agronomy Annual Meeting mimeograph. Referenced from Lull (1964).

Haneberg, W. C., 1995. Steady state groundwater flow across idealized faults, Water Resources Research, Vol. 31, No. 7, pp. 1815-1820, July 1995.

Hillel, D., 1971. Soil and Water: Physical Principles and Processes. Academic Press.

Holmes, M., Personal communication with John McCord, SNL/NM Environmental Restoration Program, Nov. 1995.

Lozinsky, R. P., J. W. Hawley, and D. W. Love, 1991. Geologic Overview and Pliocene-Quaternary History of the Albuquerque Basin, Central New Mexico, New Mexico Bureau of Mines and Minerals Resources Bulletin 137, pp. 157-162.

Lull, H. W., 1964. Ecological and Silvicultural Aspects, in Handbook of Applied Hydrology. V. T. Chow, ed., Section 6, New York: McGraw Hill.

PRC, 1990. PRC Environmental Management, Inc. ITRI Lagoon Hydrogeological Study, unpublished report prepared for the Lovelace Inhalation Toxicology Research Institute, Albuquerque, NM.

PRC, 1993. PRC Environmental Management, Inc. Alluvial Aquifer Characterization Study, unpublished report prepared for the Lovelace Inhalation Toxicology Research Institute, Albuquerque, NM.

Ramsey, J. G., 1967. Folding and Fracturing of Rocks. New York: McGraw Hill.

Reading, H. G., editor, 1978. Sedimentary Environments and Facies. New York: Elsevier.

Ritter, D. F., 1986. Process Geomorphology. Second Edition, Dubuque, Iowa: William C. Brown Publishers.

SNL/NM, 1993. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1992 Annual Report. SAND93-0681, Environmental Restoration Program, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1993 Annual Report. Environmental Restoration Program, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1994 Annual Report. Environmental Restoration Program, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Spencer, E. W., 1977. Introduction to the Structure of the EARTH. New York: McGraw Hill.

Stephens, D. B., and Associates, 1989. Laboratory Analysis of Soil Hydraulic Properties from the Chemical Waste Landfill CAP Verifications Project, prepared for Sandia National Laboratories/NM by D. B. Stephens & Associates, Albuquerque, NM.

Thomson, B. M. and G. J. Smith, 1985. Investigation of Groundwater Contamination Potential at Sandia National Laboratories, Albuquerque, NM, in Proceedings of the Fifth DOE Environmental Protection Information Meeting, Albuquerque, NM, November 6-8, 1984, CONF-841187, pp. 531-540.

Trimble, G. R., Jr., 1959. A Problem with Analysis and Program for Watershed-Management Research, U.S. Forest Service, NE Forest Experiment Station, Station Paper 116, 1959. Referenced from Lull (1964).

USGS, 1993. United States Geological Survey. Installation Restoration Program, Stage 2A, RI/FS Technical Report for Kirtland Air Force Base, USGS Water Resources Division, Albuquerque, NM.

USDA, 1955. United States Department of Agriculture. USDA Yearbook, pp. 4-6.

Whitten, D. G. A., and J. R. V. Brooks, 1976. The Penguin Dictionary of Geology. Baltimore, Maryland: Penguin Books.

Wisler, C. O., and E. F. Brater, 1959. Hydrology. New York: Wiley and Sons. Referenced from Lull (1964).

Wolford, R. A., 1995. Personal communication with John McCord, SNL/NM Environmental Restoration Program, 1995.

APPENDIX A
SURFACE HYDROLOGY, SURFACE WATER QUALITY, ARROYO RECHARGE, AND A VERY LARGE-SCALE INFILTRATION TEST

Point of Contact: Ross Wolford (GRAM, Inc.)

CONTENTS

TABLES

A.1 INTRODUCTION

Surface hydrology work performed during fiscal year 1995 (FY95) included streamflow monitoring, surface water quality monitoring, neutron monitoring of infiltration beneath arroyos, surveying arroyos for infiltration and recharge characteristics, some minimal literature review and historical flood flow analysis, and a very large-scale infiltration test performed in conjunction with an aquifer test.

A.2 METEOROLOGICAL RECORDS REVIEW

A simple review of local, historical rainfall records was performed in 1995. This work uncovered some potentially significant information. Long-term (75-yr) rainfall records from the National Weather Service gage at the Albuquerque International Airport were examined to help determine how precipitation in recent years compares with long-term averages. The records suggest that annual rainfall has been substantially above average in most recent years (Figure 3.2.1-2, Section 3.2.1), though 1995 was drier than average (NOAA 1917-1995). During the preceding 6 yr, 3 yr had more than 125% of average precipitation, and 5 of those 6 yr were above average. During the most recent 18 yr, 8 yr had more than 125% of average precipitation, 12 yr were above average, and only 2 yr had less than 75% of normal precipitation. Conclusions drawn from analysis of hydrologic data over the past several years should consider the effects of this above-average rainfall. Examples of hydrologic processes that may have been affected include surface runoff, soil-water movement in the vadose zone, and aquifer recharge through arroyos. **Conclusions drawn in this report have not been adjusted based on the above-average precipitation known to exist in 1990, 1991, 1992, and 1994, which includes most years for which streamflow data are available**. Areas of aquifers that are responsive to short-term changes in recharge (particularly from arroyos) might also show some response to above-average rainfall. One such location may be the area near where Tijeras Arroyo enters Kirtland Air Force Base (KAFB).

A.3 STREAMFLOW MONITORING

Four streamflow gages installed by the Site-Wide Hydrogeologic Characterization (SWHC) Project on Arroyo del Coyote and Tijeras Arroyo were monitored throughout water-year 1995 (WY95) (WY is the period October 1 through September 30 each year) (Figure A-1). One of these gages, located just above Coyote Springs on Arroyo del Coyote, was vandalized in October 1994, and was out of service until April 20, 1995. The others functioned throughout the year. One additional gage was installed on the largest arroyo that enters Technical Area III (TA-III) near its southeast corner. The SWHC support for four U.S. Geological Survey (USGS) gages on Arroyo del Coyote and Tijeras Arroyo was terminated in 1995 due to a lack of funding.

Based on limited data and observations during WY93 through WY95, rainfall events large enough to produce runoff do not typically produce more runoff at higher elevations around KAFB. To some degree, this observation can be linked to the fraction of impermeable surfaces present on some watersheds; portions of the airport/air base/Sandia National Laboratories/New Mexico (SNL/NM) complex often produce more surface runoff in lower Tijeras Arroyo than do the approximately 80 mi^2 of the Tijeras Arroyo watershed upstream of those areas. This phenomenon is often evident in data from upper and lower USGS gages on Tijeras Arroyo (Table A-1, Figure A-1). Another example is that flows from the drainage just north of the Burn Site (Plate I) were not large enough to collect an adequate water sample for quality analysis, while several samples were obtained below the Burn Site. The higher flows below the Burn Site are largely a result of roads, parking lots, and other development at the Burn Site. However, the flows measured at Gage 3 above Coyote Springs are often disproportionately larger than those measured farther upstream at Gage 1 and Gage 2 (Table A-2, Figure A-1), though very little development exists between those areas. The flows suggest that moderately large storms are often more intense farther away from the mountains, which is possible, although counterintuitive. This variation could also be due to higher infiltration rates near the mountains, or by more road-induced runoff in the lower watershed (almost no roads are upstream of the Burn Site). Data are too sparse to draw definite conclusions. It is also known that a significant portion of small to moderately large flows infiltrate into the stream bed.

Table A-1. Streamflow Data Collected From Four Local U.S. Geological Survey Gages During Water Year 1994 (Discharge in cubic feet)

	Upper Arroyo del Coyote	Lower Arroyo del Coyote	Upper Tijeras Arroyo	Lower Tijeras Arroyo
USGS Gage #	8330565	8330567	8330569	8330580
Watershed area (mi^2)	35	39	121	122
Day				
11 May	1700	95,000	660,000	2,100,000
26 May	21,000	72,000	22,000	350,000
18 June			110,000	560,000
21 June			350,000	790,000
23 July			1000	260,000
28 July			8000	200,000
1 August	45,000	95,000	500,000	1,200,000
14 August		1700		8600
15 August	230,000	1,100,000	2,900,000	7,100,000
20 August	95,000	missing	67,000	380,000
21 August	900	missing		
26 August	120,000	missing	8600	
18 September				200,000
Total Measured	520,000	1,400,000	4,600,000	13,000,000
Acre Feet	12	32	105	300

Data for WY95 from the four USGS gages were unavailable at the time this report was generated. The WY94 data from these gages are given in Table A-1. Four new (not USGS) gages installed during WY94 measure runoff from a total watershed area of about 100 mi^2, the majority of which is from Tijeras Arroyo outside of the KAFB boundaries. About 14.7 mi^2 of the total watershed area is measured twice because the gage above Coyote Springs (Gage 3) includes the watershed areas of Gages 1 and 2. The total runoff measured at the four new gages during WY95 (including those flows passing more than one gage and thus measured twice), was about 13.65 million ft^3 (313 acre-ft [AF]) (Table A-2). To put this quantity in perspective, it is equal to an annual water supply for about 1,120 people at a use rate of 250 gal./person/day, or about 0.06 in. over the gaged watershed's surface area. This quantity is about 104% of flows passing the lower USGS gage on Tijeras Arroyo during WY94 (the prior water year). Runoff passing this USGS gage includes that generated on the majority of the KAFB watershed area, in addition to a somewhat larger off-base area.

Table A-2. Streamflow Data Collected From Four Site-Wide Hydrogeologic Characterization Gages During Water Year 1995 (Discharge in cubic feet)

Calendar Day	Date	Station 1	Station 2	Station 3	Station 4
Area (mi^2)		6.6 mi^2	8.1 mi^2	21 mi^2	about 80 mi^2
287	14 October 94	66,000	50		750,000
288	15 October 94	2800	T[a]		1,460,000
289	16 October 94	7100	T		
290	17 October 94	5100	T		
299	26 October 94	11	T		810,000
315	11 November 94	1000	T		
316	12 November 94	36,000	T		1,150,000
56	25 February 95				110,000
85	26 March 95				240,000
99	9 April 95				300,000
116	26 April 95			77,000	1,000,000
197	16 July 95				420,000
199	18 July 95		3400	6100	670,000
234	22 August 95	10	T	27,000	2,660,000
235	23 August 95	12,000	T	20,000	1,860,000
239	27 August 95	62,000	T	39,000	1,200,000
242	30 August 95			5500	
250	7 September 95				270,000
251	8 September 95	T			190,000
271	28 September 95	1200		870	160,000
272	29 September 95	25,000	T	5500	
	Total ft^3	218,221	3450	180,970	13,250,000
	Acre ft	5.01	0.08	4.15	304.18

[a]T = trace

The newest stream gage (Gage 5) was installed at the southeastern boundary of TA-III in June 1995. This gage was installed below a culvert crossing along the east boundary road and was expected to measure flows from an arroyo whose watershed includes the Optical Range and Mount Washington areas. However, this arroyo is blocked not far from the gage, and hence, what was observed was ponding, rather than measurable streamflow. This gage and arroyo are described in more detail in Section A.7.

A.4 HISTORICAL FLOOD EVALUATION

A large tree trunk (apparently a cottonwood) is lodged high on a rock above the stream channel of Arroyo del Coyote, about 0.5 mi upstream of Lovelace Road (Figure A-1). This tree trunk (log) was first reported in the 1990 groundwater monitoring report (SNL/NM 1991). Initial reconnaissance suggests that this log was deposited by flooding, probably from the Coyote Springs area. The location appears to be too dry to support cottonwoods and no living examples are in the vicinity. Because the wood has not rotted away, it was probably deposited during historical times, perhaps within the preceding 50 to 100 yr. (It is supported by rock, and hence, will not rot as fast as it would in contact with the ground.) The log is partially hollow and currently the home of a swarm of bees. The log's location was surveyed using a global positioning (satellite) system. The SNL/NM Environmental Restoration (ER) geographic information system was then used to map this log along with the stream channel geometry of the area (2-ft contours). The channel geometry in the immediate area is relatively complex. The log is perched on a rocky point that juts into the flood channel along the outside of a bend. In an ideal case, estimating the discharge that deposited this log would make use of a two-dimensional flow model that could account for eddies and the momentum-induced deepening of flow on the outside of the bend. Other inputs to this model would include at least one additional upstream high water mark and perhaps another downstream mark; we did not note such high water marks in the brief time that was allocated to evaluating this event. A major effort in quantifying this peak flow was not justified in support of SNL/NM ER, because floodplain delineation does not appear to be of major consequence to most significant ER sites. Other potential actions by SNL/NM, such as installation of major bridges, might require reevaluating this runoff event. However, to observe such a telling feature without some quantitative analysis did not seem reasonable. Therefore, a simplified analysis was performed to get a rough estimate of the peak flow that deposited this log.

The analysis was performed assuming that the channel was uniform, and the peak stage was some 2 ft lower than the highest elevation of the log in its current position. The 2-ft reduction in peak stage was based on professional judgment and was used to account for (1) the probability that the whole log was not submerged during its collision with the rock, (2) backwater effects of the channel constriction, and (3) momentum effects on the outside of a sharp curve. With this assumption, the channel top width was 132 ft, the wetted perimeter was 140 ft, the maximum depth was 7.5 ft, and the area of flow was 475 ft^2. A Manning "N" coefficient of 0.035 was selected from the literature for a winding, irregular, and clear channel (Morris and Wiggert 1972). Combining these data with the common Manning equation for open channel flow results in a flood flow estimate of 6300 ft^3/sec for the event that deposited the log. This is approximately 175% of the flow predicted by the USGS technique (Waltemeyer 1986) for a 100-yr event. Incidentally, the area of flow and discharge corresponds to a velocity of slightly over 13 ft/sec, which gives a velocity head of 2.73 ft. The head loss factor (i.e., the fraction of total velocity head lost) in a bend ranges from 0 (with a smooth transition) to slightly over 1.0 (Morris and Wiggert 1972, page 189). Given a midrange head loss factor of about 0.5, the estimated velocity head of 2.73 ft is large enough to account for almost 70% of the 2-ft head reduction used in the calculations; the rise in water on the outside of the bend due to centrifugal force could account for most of the remaining head adjustment used in this computation. It is not known when this flood occurred, but it is estimated to be within the last 50 to 100 yr based on the condition of the log. Several factors could affect the flow estimate obtained. One factor is that a flood of this magnitude would probably carry a large sediment load; fine entrained sediments would increase the viscosity of the flow. This would cause flow estimates based on peak depths to be higher than actual flows. Another consideration is that it is not known whether the log was deposited at the absolute peak water elevation that occurred during the runoff, though sediment deposits on the rock suggest that it probably was deposited very near the peak flow. Finally, the Manning "N" value used may be too low for this type of flow. Although the channel is accurately described as winding, irregular, and clean, with a flow this high the smaller, meandering, "bankfull" channel is so deeply buried beneath the flow that it may behave more like channel-bottom roughness to the flood flow than as a preferred pathway for water (i.e., the smaller channel meanders beneath the flood's flow path, so that its banks act like angled corrugations on the channel bottom). A larger "N" value would result in an inversely proportional decrease in the peak flow estimate. All things considered, the flood peak that deposited this log was probably somewhat lower than the 6300 ft^3/sec suggested by this cursory analysis.

A.5 SURFACE WATER QUALITY

Until 1994, few surface water quality samples were available for the SNL/KAFB area. Most samples that were available were representative of flows from parking lots and heavily developed areas. Efforts to obtain a more distributed set of surface water quality samples from rainfall runoff events began in May 1994. These efforts were designed to improve knowledge of background concentrations of constituents of concern, to help verify that areas thought to be free of contamination were in fact clean, and to help identify any contaminated areas that may have been overlooked. In addition, major ions were measured and subsamples gathered for stable isotope analyses to help determine sources of groundwater recharge. Based upon a request from the U.S. Department of Energy Albuquerque Operations Office (DOE/AL), samples were also gathered near the KAFB skeet range to determine if lead, antimony, or tin from the shot shells fired at the range were contaminating runoff.

Because surface runoff and areas where it is generated are thoroughly exposed to the atmosphere, water quality analysis performed by the SWHC Project focused on nonvolatile constituents. Any volatile organic chemicals that may have been present on the soil surface at some time were assumed to have evaporated and therefore would not be found in runoff. Constituents evaluated in 1995 included metals, radionuclides, and major anions (Table A-3). The locations where these samples were collected are shown in Figure A-1. The detection and reporting limits (the minimum concentrations detectable and quantifiable, respectively) of measured constituents increased substantially in WY95 samples due to a change to an in-house laboratory for most analyses. Independent, commercial laboratories performed all radionuclide analysis.

The water sampler located near the skeet range was positioned to catch surface runoff from the range itself and from areas where shot-shell pellets are visible on the soil surface. Many of these pellets have been gathered by ants to armor the tops of their anthills. Furrows present in this area indicate that much of it was plowed several years ago, possibly to bury lead shot. The sampler's location was selected to avoid dilution by channelized water from other areas. Water collected at this site should have had near maximum metals concentrations and represent a worst case situation.

No surface water samples show indications of more than trace levels of constituents of concern; some of these trace levels may be the result of laboratory errors. Samples gathered where runoff collected between the skeet range and the runoff energy dissipator along Pennsylvania Avenue showed no measurable concentrations of any principal component in "lead" shot (i.e., lead [Pb], tin [Sn], antimony [Sb]).

Stable isotopes were not measured in 1995 samples, but results from 1994 samples were returned in 1995 (Table A-3). The range of isotopic ratios measured in surface water samples was large, the number of samples small, and the period of sampling short (May 1994 to September 1994). Independently, these data may not be particularly useful for identifying recharge sources because they do not provide an estimate of annual average values in precipitation. Other researchers have recently performed independent research using stable isotopes for recharge analysis elsewhere in New Mexico. It is possible that by evaluating our data in conjunction with their data that some benefit may be derived.

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995)
(Interpretive data follows table)

	AC#0	AC#00	AC#2	AC#1
Sample No.	16364	16365	17275	17276
Date	5-25-94	5-25-94	6-19-94	6-19-94
East		447275	408321	412892
North		1457214	1455309	1453254
Metals (mg/l):				
Ag	0.0061/0.01	ND/0.01	ND/0.01	ND/0.01
Al	41.4/0.1	9.6/0.1	11.5/0.1	2.5/0.1
As	ND/0.01	0.016/0.01	ND/0.01	ND/0.01
Ba	3.9/0.01	2.3/0.01	0.78/0.01	0.17/0.01
Be	0.0091/0.002	0.0056/0.002	0.004/0.002	ND/0.002
Ca	1690.0/0.2	949.0/0.2	172.0/0.2	42.2/0.2
Cd	ND/0.005	ND/0.005	ND/0.005	ND/0.005
Co	0.021/0.01	0.01/0.01	0.013/0.01	ND/0.01
Cr	ND/0.01	ND/0.01	ND/0.01	ND/0.01
Cu	0.043/0.02	0.045/0.02	0.0097/0.02	ND/0.02
Fe	23.2/0.1	1.6/0.1	2.7/0.1	0.75/0.1
Hg	0.00016/0.0002	0.0003/0.0002	ND/0.0002	ND/0.0002
K	14.9/5.0	8.0/5.0	5.2/5.0	3.2/5.0
Mg	28/0.2	20.4/0.2	12.3/0.2	2.4/0.2
Mn	2.6/0.01	1.4/0.01	0.82/0.01	0.19/0.01
Na	2.2/5.0	3.7/5.0	1.8/5.0	0.74/5.0
Ni	0.054/0.04	ND/0.04	0.017/0.04	ND/0.04
Pb	ND/0.003	0.032/0.003	0.021/0.003	0.0094/0.003
Sb	ND/0.06	ND/0.06	ND/0.06	ND/0.06
Se	ND/0.005	0.012/0.005	0.0057/0.005	ND/0.005
Sn				
Tl	ND/0.01	ND/0.01	ND/0.01	ND/0.01
V	0.073/0.01	0.042/0.01	0.04/0.01	0.0074/0.01
Zn	0.19/0.02	0.24/0.02	0.048/0.02	0.057/0.02
Anions (mg/l):				
Br				
Cl				
F				
NO_3 as N				
PO_4 as P				
SO_4				
TSS				
TOX	0.015/0.03	0.019/0.03	0.035/0.030	
Explosives (µg/l):				
1,3-DNB	ND/0.11	ND/0.11	ND/0.11	
HMX	ND/0.8	ND/0.8	ND/0.8	
nitrobenzene	ND/0.25	ND/0.25	ND/0.25	
RDX	ND/0.84	ND/0.84	ND/0.84	
tetryl	ND/0.8	ND/0.8	ND/0.8	
2,6-DNT	ND/0.31	ND/0.31	ND/0.31	
2,4-DNT	ND/0.02	ND/0.02		
2,4,6-TNT	ND/0.11	ND/0.11	ND/0.11	
2-amino-4,6-DNT	ND/0.035	ND/0.035	ND/0.035	
4-amino-2,6-DNT	ND/0.06	ND/0.06	ND/0.06	
1,3,5-TNB	ND/0.26	ND/0.26	ND/0.26	
Radionuclides (pCi/l):				
$^{233/234}U$	16.0 B/0.55	19.0 B/0.37	1.3/0.16	1.1/0.58
^{235}U	0.72/0.48	0.4/0.43	0.3/0.12	0.21/0.36
^{238}U	20.0 B/0.55	16.0 B/0.29	1.5/0.12	1.3 B/0.36
^{228}Th				
^{230}Th	16.0/0.77	17.0/1.0	3.7/0.14	0.32/0.022
^{232}Th	15.0/0.35	20.0/0.75	3.3/0.055	0.40/0.066
^{90}Sr	4.9/20.0	1.2/16.0	3.3/3.6	-0.21/1.4
Stable Isotopes				
D/H			0	10
$^{18}O/^{16}O$			0.7	1.5

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

	AC#5	AC#3	AC#3	AC#4
Sample No.	17281	17282	17283	17284
Date	7-17-94	7-21-94	7-26-94	7-26-94
East	448171	447612	447612	449222
North	1449574	1459275	1459275	1454254
Metals (mg/l):				
Ag	ND/0.01	ND/0.01	0.0036/0.01	ND/0.01
Al	1.7/0.1	6.1/0.1	2.9/0.1	1.1/0.1
As	ND/0.01	ND/0.01	ND/0.01	ND/0.01
Ba	0.25/0.01	0.35/0.01	0.26/0.01	0.11/0.01
Be	ND/0.002	ND/0.002	ND/0.002	ND/0.002
Ca	152.0/0.2	139.0/0.2	98.6/0.2	37.1/0.2
Cd	ND/0.005	ND/0.005	ND/0.005	0.0056/0.005
Co	ND/0.01	0.0081/0.01	0.0057/0.01	ND/0.01
Cr	ND/0.01	ND/0.01	ND/0.01	ND/0.01
Cu	0.014/0.02	0.021/0.02	0.016/0.02	0.029/0.02
Fe	0.89/0.1	2.7/0.1	0.95/0.1	0.52/0.1
Hg	ND/0.0002	ND/0.0002	ND/0.0002	ND/0.0002
K	3.0/5.0	5.9/5.0	4.5/5.0	5.5/5.0
Mg	6.7/0.2	4.9/0.2	3.5/0.2	1.8/0.2
Mn	0.1/0.01	0.37/0.01	0.29/0.01	0.14/0.01
Na	3.0/5.0	ND/5.0	3.2/5.0	ND/5.0
Ni	0.01/0.04	0.0093/0.04	0.0086/0.04	ND/0.04
Pb	0.0099/0.003	0.023/0.003	0.013/0.003	0.0041/0.003
Sb	ND/0.06	ND/0.06	ND/0.06	ND/0.06
Se	0.0052/0.005	ND/0.005	ND/0.005	ND/0.005
Sn				
Tl	ND/0.01	ND/0.01	ND/0.01	ND/0.01
V	0.028/0.01	0.016/0.01	0.02/0.01	0.0098/0.01
Zn	0.028/0.02	0.047/0.02	0.035/0.02	0.097/0.02
Anions (mg/l):				
Br	ND/0.2	ND/0.2	ND/0.2	
Cl	ND/3.0	ND/3.0	ND/3.0	
F	0.8/0.1	0.39/0.1	0.11/0.1	
NO_3 as N	0.8/0.1	ND/0.1	0.11/0.1	
PO_4 as P	ND/0.5	ND/0.5	ND/0.5	
SO_4	6.7/5.0	ND/5.0	ND/5.0	
TSS			14600/50	
TOX	0.028/0.030	ND/0.03	ND/0.03	
Explosives (μg/l):				
1,3-DNB	ND/0.11	ND/0.11	ND/0.11	
HMX	ND/0.8	ND/0.8	ND/0.8	
nitrobenzene	ND/0.25	ND/0.25	ND/0.25	
RDX	ND/0.84	ND/0.84	ND/0.84	
tetryl	ND/0.8	ND/0.8	ND/0.8	
2,6-DNT	ND/0.31	ND/0.31	ND/0.31	
2,4-DNT	ND/0.02	ND/0.02	ND/0.02	
2,4,6-TNT	ND/0.11	ND/0.11	ND/0.11	
2-amino-4,6-DNT	ND/0.035	0.28/0.035	ND/0.035	
4-amino-2,6-DNT	ND/0.06	ND/0.06	ND/0.06	
1,3,5-TNB	ND/0.26	ND/0.26	ND/0.26	
Radionuclides (pCi/l):				
$^{233/234}U$	2.3 B/0.21	6.2 B/0.25	14.0/0.66	7.7/0.61
^{235}U	0.076/0.13	0.26/0.18	0.7/0.50	0.26/0.52
^{238}U	2.5/0.13	8.0 B/0.25	15/0.73	8.2/0.77
^{228}Th				
^{230}Th	2.6/0.23	8.7/0.17	22.0/0.40	10.0/0.48
^{232}Th	1.9/0.22	6.5/0.20	19.0/0.57	7.8/0.57
^{90}Sr	6.1 B/3.0	6.8/5.8	0.89/10.0	0.63/7.3
Stable Isotopes				
D/H	-42.0	-58.0	-65	
$^{18}O/^{16}O$	-5.6	-9.4	-10.3	

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

	AC#1	AC#2	AC#2	AC#4
Sample No.	17285	17286	017287	17288
Date	8-1-94	8-1-94	8-1-94	8-1-94
East	412892	408321	408321	
North	1453254	1455309	1455309	
Metals (mg/l):				
Ag	ND/0.01	ND/0.01	ND/0.01	
Al	1.5/0.1	4.5/0.1	4.6/0.1	
As	ND/0.01	ND/0.01	ND/0.01	
Ba	0.098/0.01	0.22/0.01	0.22/0.01	
Be	ND/0.002	ND/0.002	ND/0.002	
Ca	21.6/0.2	51.8/0.2	51.5/0.2	
Cd	ND/0.005	ND/0.005	ND/0.005	
Co	ND/0.01	0.0042/0.01	ND/0.01	
Cr	ND/0.01	ND/0.01	ND/0.01	
Cu	0.013/0.02	0.0091/0.02	0.01/0.02	
Fe	0.58/0.1	1.8/0.1	1.8/0.1	
Hg	0.0001/0.0002	ND/0.0002	ND/0.0002	
K	3.9/5.0	3.8/5.0	3.6/5.0	
Mg	2.0/0.2	4.8/0.2	4.7/0.2	
Mn	0.071/0.01	0.25/0.01	0.25/0.01	
Na	ND/5.0	ND/5.0	ND/5.0	
Ni	ND/0.04	ND/0.04	ND/0.04	
Pb	0.013/0.003	0.011/0.003	0.011/0.003	
Sb	ND/0.06	ND/0.06	ND/0.06	
Se	ND/0.005	ND/0.005	ND/0.005	
Sn				
Tl	ND/0.01	ND/0.01	ND/0.01	
V	0.004/0.01	0.03/0.01	0.03/0.01	
Zn	0.2/0.02	0.06/0.02	0.06/0.02	
Anions (mg/l):				
Br	ND/0.2	ND/0.2	ND/0.2	ND/0.2
Cl	ND/3.0	ND/3.0	ND/3.0	ND/3.0
F	ND/0.1	ND/0.1	0.1/0.1	0.5/0.1
NO_3 as N	0.33/0.1	0.4/0.1	0.4/0.1	1.4/0.1
PO_4 as P	ND/0.5	ND/0.5	ND/0.5	ND/0.5
SO_4	ND/5.0	ND/5.0	ND/5.0	ND/5.0
TSS	1810/20	17,000/50	29,200/100	15,100/100
TOX	ND/0.03	ND/0.03	ND/0.03	0.034/0.03
Explosives (μg/l):				
1,3-DNB	ND/0.11	ND/0.11	ND/0.11	ND/0.11
HMX	ND/0.8	ND/0.8	ND/0.8	ND/0.8
nitrobenzene	ND/0.25	ND/0.25	ND/0.25	ND/0.25
RDX	ND/0.84	ND/0.84	ND/0.84	ND/0.84
tetryl	ND/0.8	ND/0.8	ND/0.8	ND/0.8
2,6-DNT	ND/0.31	ND/0.31	ND/0.31	ND/0.31
2,4-DNT	ND/0.02	ND/0.02	ND/0.02	ND/0.02
2,4,6-TNT	ND/0.11	ND/0.11	ND/0.11	ND/0.11
2-amino-4,6-DNT	0.038/0.035	ND/0.035	ND/0.035	0.038/0.035
4-amino-2,6-DNT	ND/0.06	ND/0.06	ND/0.06	ND/0.06
1,3,5-TNB	ND/0.26	ND/0.26	ND/0.26	ND/0.26
Radionuclides (pCi/l):				
$^{233/234}U$	0.83/0.02	4.0/0.06	4.1/0.07	
^{235}U	0.029/0.05	0.13/0.14	0.08/0.07	
^{238}U	0.83/0.02	4.1/0.17	4.5/0.07	
^{228}Th				
^{230}Th	1.2/0.04	5.3/0.17	5.5/0.16	
^{232}Th	1.4/0.04	6.4/0.17	6.1/0.11	
^{90}Sr	0.26/1.4	-2.3/4.6	-0.34/3.9	
Stable Isotopes				
D/H	-26.0			-42
$^{18}O/^{16}O$	-4.5			-6.7

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

Sample No.	AC#6 017289	AC#10 17290	AC#4 17291	AC#6 17292
Date	8-1-94	8-14-94	8-15-94	8-15-94
East		414735	449222	450339
North		1446522	1454254	1456185
Metals (mg/l):				
Ag	ND/0.01	ND/0.01	ND/0.01	ND/0.01
Al	3.5/0.1	0.86/0.1	1.1/0.1	7.9/0.1
As	ND/0.01	ND/0.01	ND/0.01	ND/0.01
Ba	0.43/0.01	0.056/0.01	0.089/0.01	0.51/0.01
Be	ND/0.002	ND/0.002	ND/0.002	ND/0.002
Ca	137/0.2	17.2/0.2	36.1/0.2	123.0/0.2
Cd	ND/0.005	ND/0.005	ND/0.005	ND/0.005
Co	0.0058/0.01	ND/0.01	ND/0.01	0.0087/0.01
Cr	ND/0.01	ND/0.01	ND/0.01	ND/0.01
Cu	0.096/0.02	ND/0.02	0.006/0.02	0.011/0.02
Fe	0.82/0.1	0.34/0.1	0.43/0.1	2.30/0.1
Hg	ND/0.0002	ND/0.0002	ND/0.0002	ND/0.0002
K	5.3/5.0	5.0/5.0	2.6/5.0	4.3/5.0
Mg	4.2/0.2	1.4/0.2	1.9/0.2	5.0/0.2
Mn	0.45/0.01	0.051/0.01	0.073/0.01	0.72/0.01
Na	4.0/5.0	ND/5.0	1.7/5.0	1.2/5.0
Ni	0.0078/0.04	0.0085/0.04	0.05/0.04	0.018/0.04
Pb	0.04/0.003	0.0028/0.003	0.0032/0.003	0.023/0.003
Sb	ND/0.06	ND/0.06	ND/0.06	ND/0.06
Se	ND/0.011	ND/0.005	ND/0.005	ND/0.005
Sn				
Tl	ND/0.01	ND/0.01	ND/0.01	ND/0.01
V	0.016/0.01	0.0079/0.01	0.012/0.01	0.031/0.01
Zn	0.17/0.02	0.081/0.02	0.058/0.02	0.081/0.02
Anions (mg/l):				
Br		ND/0.2	ND/0.2	ND/0.2
Cl		ND/3.0	ND/3.0	ND/3.0
F		0.22/0.1	0.39/0.1	0.4/0.1
NO_3 as N		0.4/0.1	0.59/0.1	0.51/0.1
PO_4 as P		ND/0.5	ND/0.5	ND/0.5
SO_4		ND/5.0	ND/5.0	ND/5.0
TSS		524/10	344/10	25,700/10
TOX		ND/0.03	ND/0.03	ND/0.03
Explosives (μg/l):				
1,3-DNB		ND, ND/0.11	ND, ND/0.11	ND, ND/0.11
HMX		ND, ND/0.8	ND, ND/0.8	ND, ND/0.8
nitrobenzene		ND, ND/0.25	ND, ND/0.25	ND, ND/0.25
RDX		ND, ND/0.84	ND, ND/0.84	ND, ND/0.84
tetryl		ND, ND/0.8	ND, 0.6/0.8	1.9, ND/0.80
2,6-DNT		ND, ND/0.31	ND, ND/0.31	ND, ND/0.31
2,4-DNT		ND, ND/0.02	ND, ND/0.02	ND, ND/0.011
2,4,6-TNT		0.064, ND/011	ND, ND/0.11	0.11, ND/0.02
2-amino-4,6-DNT		ND, 0.027/0.035	ND, ND/0.035	ND, ND/0.035
4-amino-2,6-DNT		ND, ND/0.06	ND, ND/0.06	ND, ND/0.06
1,3,5-TNB		ND, ND/0.26	ND, ND/0.26	ND, ND/0.26
Radionuclides (pCi/l):				
$^{233/234}U$		1.1 B/0.02	0.67 B/0.05	22.0 B/0.74
^{235}U		0.07/0.04	0.03/0.06	0.98 B/0.22
^{238}U		1.1 B/0.02	0.94 B/0.06	42.0 B/0.49
^{228}Th				
^{230}Th		1.2 B/0.04	0.48/0.13	27.0/0.75
^{232}Th		1.1/0.04	0.44/0.11	24.0/0.59
^{90}Sr		0.88/1.1	2.4/1.2	19.0/15.0
Stable Isotopes				
D/H		-64.0	-66.0	-71.0
$^{18}O/^{16}O$		-9.4	-9.5	-10.5

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

Sample No. Date East North	AC#9 017293 8-15-94 453095 1459085	17294 8-25-94 NA NA	AC#3 017295 9-13-94 447612 1459275	21641 7-20-95 411210 1467026
Metals (mg/l):				
Ag	ND/0.01	ND/0.01	ND/0.01	ND/0.1
Al	0.36/0.1	ND/0.1	0.16/0.1	0.225/0.2
As	ND/0.01	ND/0.01	ND/0.01	ND/0.5
Ba	0.029/0.01	ND/0.01	0.050/0.01	0.145/0.1
Be	ND/0.002	ND/0.002	ND/0.002	ND/0.03
Ca	12.1/0.2	ND/0.2	17.8/0.2	24/0.2
Cd	ND/0.005	ND/0.005	ND/0.005	ND/0.1
Co	ND/0.01	ND/0.01	ND/0.01	ND/0.1
Cr	ND/0.01	ND/0.01	ND/0.01	ND/0.1
Cu	0.0036/0.02	ND/0.02	0.021/0.02	ND/0.2
Fe	0.11/0.1	ND/0.1	0.088/0.1	ND/0.05
Hg	ND/0.0002	ND/0.0002	ND/0.0002	ND/0.002
K	0.96/5.0	ND/5.0	4.3/5.0	NA
Mg	0.38/0.2	ND/0.2	1.3/0.2	3.5/0.1
Mn	0.014/0.01	ND/0.01	ND/0.01	ND/0.1
Na	ND/5.0	ND/5.0	ND/5.0	NA
Ni	ND/0.04	0.0078/0.04	ND/0.04	ND/0.04
Pb	0.0029/0.003	ND/0.003	ND/0.003	ND/0.1
Sb	ND/0.06	ND/0.06	ND/0.06	ND/0.1
Se	ND/0.005	ND/0.005	ND/0.005	ND/0.5
Sn				ND/1.0
Tl	ND/0.01	0.011/0.01	0.0039/0.01	ND/2.0
V	0.0057/0.01	0.004/0.01	0.0022/0.01	ND/0.1
Zn	0.014/0.02	ND/0.02	0.0097/0.02	ND/0.1
Anions (mg/l):				
Br	ND/0.2	ND/0.2	ND/0.2	
Cl	ND/3.0	ND/3.0	ND/3.0	
F	ND/0.1	ND/0.1	ND/0.1	
NO_3 as N	ND/0.1	ND/0.1	0.21/0.1	
PO_4 as P	ND/0.5	ND/0.5	ND/0.5	
SO_4	ND/5.0	ND/5.0	ND/5.0	
TSS	996/20			
TOX	ND/0.03	ND/0.03	0.032/0.03	
Explosives (μg/l):				
1,3-DNB	ND, ND/0.11	ND/0.11	ND/0.11	
HMX	ND, ND/0.8	ND/0.8	ND/0.8	
nitrobenzene	ND, ND/0.25	ND/0.25	ND/0.25	
RDX	ND, ND/0.84	ND/0.84	ND/0.84	
tetryl	ND, ND/0.8	ND/0.8	ND/0.6	
2,6-DNT	ND, ND/0.31	ND/0.31	ND/0.31	
2,4-DNT	ND, ND/0.02	ND/0.02	ND/0.02	
2,4,6-TNT	ND, ND/0.11	ND/0.11	ND/0.11	
2-amino-4,6-DNT	0.072, 0.039/0.035	ND/0.035	ND/0.035	
4-amino-2,6-DNT	ND, ND/0.06	ND/0.06	ND/0.06	
1,3,5-TNB	ND, ND/0.26	ND/0.26	ND/0.26	
Radionuclides (pCi/l):				
$^{233/234}U$	0.55 B/0.02	0.17 B/0.06	4.76/2.86	
^{235}U	0.02/0.04	0.02/0.03	0.27/2.33	
^{238}U	0.48 B/0.02	0.14 B/0.06	0.26/2.02	
^{228}Th			4.81/0.72	
^{230}Th	0.36 B/0.02	0.05/0.04	1.22/0.68	
^{232}Th	0.29/0.06	0.03/0.08	4.09/0.54	
^{90}Sr	3.2/1.4	1.7/2.7	0.56 U/2.31	
Stable Isotopes				
D/H	-80.0			
$^{18}O/^{16}O$	-11.3			

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

Sample No. Date East North	25122 7-20-95 404171 1465782	25123 8-22-95 404171 1465782	25123 dup 8-22-95 404171 1465782	25124 8-22-95 416418 1470339
Metals (mg/l):				
Ag	ND/0.1	ND, ND/0.1	ND, ND/0.1, 0.01	ND/0.1
Al	0.67/0.2	ND, 0.048/0.2	ND, 0.1/0.2, 0.1	ND/0.2
As	ND/0.5	ND, ND/0.5	ND/0.5	ND/0.5
Ba	0.49/0.1	ND, 0.08/0.1	ND, 0.09/0.1, 0.1	ND/0.1
Be	ND/0.03	ND, ND/0.03	ND/0.03	ND/0.03
Ca	56/0.2	71, 43/0.2	37, 44/0.2	43/0.2
Cd	ND/0.1	ND, ND/0.1	ND/0.1	ND/0.1
Co	ND/0.1	ND, ND/0.1	ND/0.1	ND/0.1
Cr	ND/0.1	ND, ND/0.1	ND/0.1	ND/0.1
Cu	ND/0.2	ND, 0.01 J/0.2	ND/0.2	ND/0.2
Fe	0.37/0.05	ND, 0.08/0.05	ND, 0.13/0.05, 0.01	ND/0.05
Hg	ND/0.002	ND, ND/0.002, 0.002	ND, ND/0.002, 0.002	ND/0.002
K		NA, 5.8/5	NA, 5.9/5	
Mg	9.6/0.1	9, 5/0.1	4.1/0.1	3.4/0.1
Mn	0.74/0.1	1.2, 0.04/0.1	ND, 0.07/0.1, 0.01	ND/0.1
Na	NA	NA, 11.9/5	11.3/5	
Ni	ND/0.04	ND, ND/0.04	ND/0.04	ND/0.04
Pb	ND/0.1	ND, ND/0.1	ND/0.1	ND/0.1
Sb	ND/0.1	ND, ND/0.1	ND/0.1	ND/0.1
Se	ND/0.5	ND, ND/0.5	ND, ND/0.5, 0.005	ND/0.5
Sn	NA	ND/1.0	ND/1.0	ND/1.0
Tl	ND/2.0	ND, 0.011/2.0	ND, 0.011/2.0, 0.01	ND/2.0
V	ND/0.1	ND, 0.006 J/0.1	0.007, ND/0.01, 0.1	ND/0.1
Zn	0.16/0.1	ND, 0.003 J/0.1	ND, ND/0.02, 0.1	ND/0.1
Anions (mg/l):				
Br			ND	ND
Cl			22.3	10.09
F			0.31	0.23
NO_3 as N			12.42	4.45
PO_4 as P			ND	ND
SO_4			37.1	20.83
TSS	1560			
TOX				
Explosives (μg/l):				
1,3-DNB				
HMX				
nitrobenzene				
RDX				
tetryl				
2,6-DNT				
2,4-DNT				
2,4,6-TNT				
2-amino-4,6-DNT				
4-amino-2,6-DNT				
1,3,5-TNB				
Radionuclides (pCi/l):				
$^{233/234}U$	1.13/0.16	1.86 B/0.25	1.19 B/0.14	0.27 B/0.10
^{235}U	ND/0.22	0.093/0.18	ND/0.16	ND/0.14
^{238}U	0.64 B/0.24	1.33 B/0.16	2.18 B/0.12	0.20 B/0.13
^{228}Th	ND/0.15	ND B/0.08	0.16 B J/0.17	ND B/0.19
^{230}Th	0.08 J/0.15	ND/0.15	ND/0.17	0.11/0.09
^{232}Th	ND/0.15	ND B/0.11	ND B/0.10	0.07 B J/0.11
^{90}Sr	1.24 B/1.00		2.54/1.0	0.95 J/1.0
Stable Isotopes				
D/H				
$^{18}O/^{16}O$				

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

Sample No. Date East North	25125 8-22-95 404171 1465782	25126 8-22-95 404171 1465782	25127 8-22-95 435430 1463661	25128 8-22-95 434717 1456968
Metals (mg/l):				
Ag	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Al	ND/0.2	ND/0.2	ND/0.2	ND/0.2
As	ND/0.5	ND/0.5	ND/0.5	ND/0.5
Ba	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Be	ND/0.03	ND/0.03	ND/0.03	ND/0.03
Ca	38/0.2	43/0.2	12/0.2	19/0.2
Cd	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Co	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Cr	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Cu	ND/0.2	ND/0.2	ND/0.2	ND/0.2
Fe	ND/0.05	ND/0.05	ND/0.05	ND/0.05
Hg	ND/0.002	ND/0.002	ND/0.002	ND/0.002
K	NA	NA	NA	
Mg	4.1/0.1	4.6/0.1	0.21 J/0.1	1.3/0.1
Mn	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Na	NA	NA	NA	
Ni	ND/0.04	ND/0.04	ND/0.04	ND/0.04
Pb	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Sb	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Se	ND/0.5	ND/0.5	ND/0.5	ND/0.5
Sn	ND/1.0	ND/1.0	ND/1.0	ND/1.0
Tl	ND/2.0	ND/2.0	ND/2.0	ND/2.0
V	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Zn	ND/0.1	ND/0.1	ND/0.1	ND/0.1
Anions (mg/l):				
Br	ND	ND	ND	ND, ND
Cl	15.37	14.19	0.63	0.72, 3.65/0.5
F	0.34	0.35	0.09	0.1
NO_3 as N	8.85	8.01	1.10	ND, ND
PO_4 as P	ND	ND	ND	ND, ND
SO_4	27.63	26.97	3.10	4.37,5.8/0.5
TSS				
TOX				
Explosives (μg/l):				
1,3-DNB				
HMX				
nitrobenzene				
RDX				
tetryl				
2,6-DNT				
2,4-DNT				
2,4,6-TNT				
2-amino-4,6-DNT				
4-amino-2,6-DNT				
1,3,5-TNB				
Radionuclides (pCi/l):				
$^{233/234}U$	1.60 B/0.10	1.53 B/0.13	0.36 B/0.13	0.43 B/0.10
^{235}U	ND/0.08	ND/0.15	0.09/0.13	ND/0.08
^{238}U	1.35 B/0.10	0.91 B/0.13	0.78 B/0.10	0.63 B/0.11
^{228}Th	0.07 B J/0.13	1.67/0.06	ND/0.0	ND/0.31
^{230}Th	0.33/0.24	0.18/0.14	0.24/0.19	2.0/0.23
^{232}Th	ND B/0.09	ND B/0.04	ND/0.08	0.23 B/0.10
^{90}Sr	3.46/1.0	2.98/1.0	0.84 J/1.0	4.69/1.0
Stable Isotopes				
D/H				
$^{18}O/^{16}O$				

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Continued)

Sample No. Date East North	25129 8-23-95 411210 1467026	25130 8-27-95 454523 1458350	25131 8-27-95 452323 1457062	25137 9-18-95 434733 1441087
Metals (mg/l):				
Ag	ND/0.1	ND/0.1	ND/0.1	
Al	ND/0.2	ND/0.2	1.2/0.2	
As	ND/0.5	ND/0.5	ND/0.5	
Ba	ND/0.1	ND/0.1	ND/0.1	
Be	ND/0.03	ND/0.03	ND/0.03	
Ca	15/0.2	22, 23/0.2	23/0.2	
Cd	ND/0.1	ND/0.1	ND/0.1	
Co	ND/0.1	ND/0.1	ND/0.1	
Cr	ND/0.1	ND/0.1	ND/0.1	
Cu	ND/0.2	ND/0.2	ND/0.2	
Fe	ND/0.05	ND/0.05	ND/0.05	
Hg	ND/0.002	ND/0.002	ND/0.002	
K	NA	NA	NA	
Mg	2/0.1	0.73, 0.77/0.1	0.69/0.1	
Mn	ND/0.1	ND/0.1	ND/0.1	
Na	NA	NA	NA	
Ni	ND/0.04	ND/0.04	ND/0.04	
Pb	ND/0.1	ND/0.1	ND/0.1	
Sb	ND/0.1	ND/0.1	ND/0.1	
Se	ND/0.5	ND/0.5	ND/0.5	
Sn	ND/1.0	ND/1.0	ND/1.0	
Tl	ND/2.0	ND/2.0	ND/2.0	
V	ND/0.1	ND/0.1	ND/0.1	
Zn	ND/0.1	ND/0.1	ND/0.1	
Anions (mg/l):				
Br		ND	ND	
Cl		0.81	0.23	
F		0.06	0.2	
NO_3 as N		ND	2.28	
PO_4 as P		ND	ND	
SO_4		1.53	3.67	
TSS				3290
TOX				
Explosives (μg/l):				
1,3-DNB				
HMX				
nitrobenzene				
RDX				
tetryl				
2,6-DNT				
2,4-DNT				
2,4,6-TNT				
2-amino-4,6-DNT				
4-amino-2,6-DNT				
1,3,5-TNB				
Radionuclides (pCi/l):				
$^{233/234}U$				0.17 J/0.23
^{235}U				ND/0.24
^{238}U				0.28/0.23
^{228}Th				1.52/0.10
^{230}Th				0.21 B/0.08
^{232}Th				ND/0.03
^{90}Sr				1.64/0.70
Stable Isotopes				
D/H				
$^{18}O/^{16}O$				

Table A-3. Surface Water Quality Data Collected by the SWHC Project (1994 to 1995) (Interpretive data follows table) (Concluded)

Sample No. Date East North	25138 9-28-95 equipment blank	25139 9-28-95	25139 dup 9-28-95
Metals (mg/l):			
Ag			
Al			
As			
Ba			
Be			
Ca			
Cd			
Co			
Cr			
Cu			
Fe			
Hg			
K			
Mg			
Mn			
Na			
Ni			
Pb			
Sb			
Se			
Sn			
Tl			
V			
Zn			
Anions (mg/l):			
Br			
Cl			
F			
NO_3 as N			
PO_4 as P			
SO_4			
TSS	ND	940	1170
TOX			
Explosives (μg/l):			
1,3-DNB			
HMX			
nitrobenzene			
RDX			
tetryl			
2,6-DNT			
2,4-DNT			
2,4,6-TNT			
2-amino-4,6-DNT			
4-amino-2,6-DNT			
1,3,5-TNB			
Radionuclides (pCi/l):			
$^{233/234}U$	ND/0.09	0.21/0.10	0.72/0.08
^{235}U	ND/0.07	ND/0.08	ND/0.06
^{238}U	ND/0.03	0.17/0.03	0.39/0.06
^{228}Th	1.34/0.15	1.39/0.28	1.4/0.11
^{230}Th	ND B/0.08	ND B/0.1	0.16 B/0.06
^{232}Th	ND/0.13	ND/0.03	ND/0.08
^{90}Sr	ND/0.39	1.40/0.44	1.54/0.46
Stable Isotopes			
D/H			
$^{18}O/^{16}O$			

Explanation and list of symbols used in Table A-3:

Concentration units are shown along the left side with species type. The values following the slash (/) are reporting (quantitation) limits, except metals analysis in 1995, where they are detection limits.

Duplicate analyses were run on some samples; a chloride value such as "6,7/3" indicates concentrations of 6 mg/l from one analysis, 7 mg/l from a second analysis, and a reporting limit of 3 mg/l.

B	Analyte was also detected in analysis of blank where none should be present
East	State Plane Coordinates; number of feet east of standard baseline
DNB	Dinitro benzene
DNT	Dinitro toluene
ND	Not detected
HMX	An explosive tradename
J	Value lower than reporting or quantitation limit
NA	Not analyzed or not applicable
North	State Plane coordinates; number of feet north of standard baseline
RDX	An explosive tradename
tetryl	An explosive tradename
TNB	Trinitro benzene
TNT	2,4,6-trinitro toluene
TOX	Total organic halogen
TSS	Total suspended sediment
U	Value lower than reporting or quantitation limit (essentially the same as "J," different laboratory)

A.6 NEUTRON MONITORING OF EVENTS IN TIJERAS ARROYO

Soil water contents at five neutron access tubes within and adjacent to Tijeras Arroyo were monitored throughout the year. These tubes provided usable data for depths from the soil surface to maximum depths between about 40 ft to 80 ft, depending on the particular tube. Particular emphasis was given to measurements tracking the reduction in water contents following the cessation of runoff events. This decline in total water content through the soil profile provides a direct indication of recharge volume (assuming minimal evaporation) for that event. In addition, water content data collected over time provided calibration data for an unsaturated flow and transport model that is anticipated to be used in FY96.

Three distinctive types of materials are monitored at the Tijeras Arroyo site. Tubes NA-2 and NA-3 (Figure A-1) are located within the main stream channel and pass through a relatively massive layer of fine silt or clay at depths of 5 ft to 9 ft. Water contents of soils above this fine material respond rapidly to arroyo runoff, while little evidence of the runoff events appears in soils beneath the fines. Tube NA-4 is also located within the main stream channel, but no indication of a fine layer was noted during its installation. Soils at the NA-4 site respond throughout the profile soon after runoff begins. Increases in soil water content were observed at depths of 20 ft in Tube NA-4 within 2 hr of the end of a 2-hr runoff event in September 1995. Tubes NA-6 and NA-7 are located about 50 ft and 25 ft, respectively, outside of the edge of the main stream channel. Water contents in the upper 3 ft at Tube NA-6 respond to rainfall, but no response to streamflow is evident at any depth in this tube. A much-delayed, small response to streamflow is apparent at depths of about 50 ft in Tube NA-7. This indicates that the ratio of horizontal to vertical movement of infiltrating arroyo waters at this location is less than 0.5.

Neutron access tubes were installed to the maximum depth possible given the equipment used and the conditions encountered (Fritts 1994). Each of these access tubes terminate at a different total depth. In addition, backfill around Tube NA-4 appears to be bridged at a depth of about 40 ft, which makes measurements below this point unreliable (SNL/NM 1995). In spite of these different total depths, cumulative water contents measured for the whole profile at each tube can be used to estimate the amount of water that drains to recharge the aquifer following each runoff event. This year's estimates of peak water additions and of the rapid response of soil water contents at depth following runoff were improved over previous estimates by taking measurements into the night following several runoff events.

Cumulative water contents for the total (reliable) measured profile of each tube over time are given for Tubes NA-2, NA-3, NA-4, and NA-7 (Figure A-2). The cumulative, incremental decreases (i.e., the sum of each peak water content minus the subsequent minimum before the next rise) for NA-2, NA-3, and NA-4 are 1.56 ft, 1.61 ft, and 6.0 ft, respectively. These figures represent the measured aquifer recharge that can be calculated from these data alone; observations of these profiles and surface soil conditions suggest evaporation is relatively small. However, not all runoff events measured in Tijeras Arroyo are represented by these data. Notably, 6 "peaks" are visible on the plots for Tubes NA-2 and NA-3, while 8 "peaks" are visible on the plot for Tube NA-4; in contrast, Table A-2 suggests measurable streamflow occurred some 15 times in Tijeras Arroyo at this location during WY95. The discrepancy is due to events that occurred in the evening or on weekends that either went unnoticed or occurred when other tasks prohibited taking neutron measurements. Assuming the volume of recharge per event is the same for measured and unmeasured events, this would indicate annual recharge was 2.5 times larger than measured for Tubes NA-2 and NA-3 (6 measured events of 15 total), and

1.88 times larger at Tube NA-4 (8 measured events of 15 total). Total estimated annual recharge is 3.9 ft at NA-2, 4.0 ft at NA-3, and 11.25 ft at NA-4.

Except for the uppermost arroyo soils exposed to evaporation, minimum water contents over the year tend to be about 12% by volume. Immediately following large runoff events, peak soil water contents appear to be about 25%. Therefore, the maximum volume of water that can be added to these soils is about 13%, when they change from most dry to most wet. Unless substantial time passes between runoff events, the volume of available storage space will be smaller. Figure A-3 suggests that average soil water content following runoff in Tijeras Arroyo may increase by about 7%. If the volume of soil affected by this increase during each event could be known, total arroyo recharge could be estimated quite accurately. With this in mind, an attempt to identify the affected soil volume was undertaken (Section A.7).

A.7 ARROYO SURVEYS AND ARROYO RECHARGE ESTIMATION

A number of small-scale infiltration tests were performed on surface soils within arroyos during the summer of 1993. Results of these tests were reported previously, but in general suggested relatively uniform infiltration rates of about 15 to 30 ft/day (SNL/NM 1994). A walkover survey of arroyos with some limited additional infiltration testing was planned to permit extrapolation of these results to arroyos throughout the SNL/KAFB area. The intent was to categorize the texture of surface materials and determine the total area of arroyo bottoms exposed to infiltrating water to determine the total volume and spatial distribution of arroyo recharge.

Prior to the initiation of the arroyo survey, neutron monitoring of arroyo infiltration events indicated that buried fine layers beneath the arroyo surface influenced recharge more than did infiltration rates through the surficial layers (SNL/NM 1995). With this in mind, the survey was extended to identify fine-textured layers beneath the channels and to perform infiltration rate tests within those layers rather than in the coarse, overlying materials (typically medium to coarse sands).

Walkover surveys (length, width, textural analysis of surface materials) were performed over the entire length of Tijeras Arroyo within SNL/KAFB boundaries and along Arroyo del Coyote between No-Sweat Boulevard at Madera Canyon and the junction of Arroyo del Coyote with Tijeras Arroyo (Rust Geotech 1995, Kautsky et al. 1995). These surveys included measuring the bank-full-channel width and collecting a soil sample for sieve analysis every 500 ft of channel length, and attempting to locate fine textured layers at intervals of (generally) 3500 ft of channel length. No effort to locate fine materials was made upstream of the Lovelace Road bridge on Arroyo del Coyote. Hand shovels and hand augers were used to locate fine textured layers to depths of 10 ft, and infiltration tests were performed at each of these excavated sites. When fine-textured layers were discovered, the infiltration tests were performed in those layers; when no fine materials were encountered, infiltration tests were performed on surface materials. In addition, laboratory analyses of saturated hydraulic conductivity (K_s) were performed on small samples from these sites. Depths where field infiltration tests were performed did not uniformly match the depth sampled for laboratory K_s measurements (Table A-4), and the laboratory analyses were performed on repacked samples.

Infiltration rates measured in coarse-textured, surface soils averaged 28 ft/day, while those in the fine-texture layers averaged about 0.14 ft/day. The fine-textured layer infiltration rates are similar to those expected for silts, which is in agreement with the (unreported) results of sieve analysis (Table A-4).

Table A-4. Results of Site-Wide Hydrogeologic Characterization Infiltration Tests and Saturated Hydraulic Conductivity Measurements for Surface and Subsurface Arroyo Soils[a]

Date	Infiltration (ft/day)	Saturated Hydraulic Conductivity (ft/day)	Depth (ft)	Location (Figure A-1)
7/30/93	36		0	Tijeras Arroyo 0.2 mi above Pennsylvania bridge
8/04/93	69		0	Above culvert on Arroyo del Coyote at balloon site
8/10/93	26		0	Canyon N of balloon site
8/11/93	13		0	Burn Site Spring Arroyo 75 yards E of Burn Site
8/12/93	10		0	Arroyo SE of Burn Site, halfway between firebreak edge and Burn Site
8/12/93	30		0	1000 ft above No-Sweat Boulevard on Burn Site Arroyo
8/13/93	52		0	Arroyo del Coyote 650 ft below Lovelace Road Bridge
8/16/93	30		0	120 ft upstream of last S turn off Mt. Washington Road, SE of Optical Range
8/17/95	31		0	Slightly upstream of 8/16/93 sample
8/18/93	20		0	Tijeras Arroyo 1500 ft below upstream KAFB boundary
8/18/93	26		0	Tijeras Arroyo 1500 ft below upstream KAFB boundary
9/10/93	39		0	Tijeras Arroyo 1500 ft below upstream KAFB boundary
9/10/93	36		0	Tijeras Arroyo 1500 ft below upstream KAFB boundary
2/95	48		0	Arroyo del Coyote, 33,500 ft below No-Sweat Boulevard
2/95		118	0.0-3.5	Arroyo del Coyote, 33,500 ft below No-Sweat Boulevard
2/95	94		0	Arroyo del Coyote, 39,000 ft below No-Sweat Boulevard
2/95	24		4.5	Arroyo del Coyote, 39,000 ft below No-Sweat Boulevard
2/95		29	0.0-3.0	Arroyo del Coyote, 39,000 ft below No-Sweat Boulevard
2/95		1	4.5-5.0	Arroyo del Coyote, 39,000 ft below No-Sweat Boulevard
2/95	4		6.4	Arroyo del Coyote, 42,500 ft below No-Sweat Boulevard
2/95		60	0.0-3.0	Arroyo del Coyote, 42,500 ft below No-Sweat Boulevard
2/95		0.27	6.4-6.66	Arroyo del Coyote, 42,500 ft below No-Sweat Boulevard
2/95	0.34		1.33	Arroyo del Coyote, 46,000 ft below No-Sweat Boulevard
2/95		0.06	1.3-3.0	Arroyo del Coyote, 46,000 ft below No-Sweat Boulevard
2/95	34		0	Arroyo del Coyote, 49,500 ft below No-Sweat Boulevard
2/95		25	0.0-2.5	Arroyo del Coyote, 49,500 ft below No-Sweat Boulevard
2/95	28		0	Tijeras Arroyo at north KAFB boundary fence
2/95		25	0.0-3.5	Tijeras Arroyo at north KAFB boundary fence
2/95		2	0.0-3.0	Tijeras Arroyo 3500 ft downstream of north KAFB boundary fence
2/95		0.0005	8.2-8.5	Tijeras Arroyo 3500 ft downstream of north KAFB boundary fence
2/95	0.18		3.08	Tijeras Arroyo 7000 ft downstream of north KAFB boundary fence
2/95		0.009	3.1-4.1	Tijeras Arroyo 7000 ft downstream of north KAFB boundary fence
2/95	26		0	Tijeras Arroyo 10,500 ft downstream of north KAFB boundary fence
2/95		31	0.0-5.5	Tijeras Arroyo 10,500 ft downstream of north KAFB boundary fence
2/95	0.06		1	Tijeras Arroyo 14,000 ft downstream of north KAFB boundary fence
2/95		0.04	1.0-2.5	Tijeras Arroyo 14,000 ft downstream of north KAFB boundary fence
2/95	26		0	Tijeras Arroyo 17,500 ft downstream of north KAFB boundary fence
2/95		10.6	0.0-2.7	Tijeras Arroyo 17,500 ft downstream of north KAFB boundary fence
2/95	0.28		1.5	Tijeras Arroyo 21,000 ft downstream of north KAFB boundary fence
2/95		0.003	1.5-2.5	Tijeras Arroyo 21,000 ft downstream of north KAFB boundary fence
2/95	1.7		2.58	Tijeras Arroyo 24,500 ft downstream of north KAFB boundary fence
2/95		29	2.6-3.4	Tijeras Arroyo 24,500 ft downstream of north KAFB boundary fence

[a] Saturated measurements were done on small samples in the laboratory.

Observed runoff events have typically been 2 to 4 hr in length. At an infiltration rate of 15 ft/day, 2.5 ft of water could enter a coarse textured arroyo soil in 4 hr. Infiltration rates through silt layers in the arroyos are typically between less than 1 cm/day to a few centimeters per day. Therefore, where silt layers underlie coarse textured arroyo bottom materials, the silt layers ultimately control infiltration once the overlying layers become saturated. Prior to this saturation, water enters the coarse materials at nearly the coarse materials' infiltration rate, which is up to several hundred times higher than that of the silt. Maximum infiltration through silt layers during a 4-hr period is typically a fraction of 1 cm. Therefore, in most cases, drainage through the silt layers can practically be ignored in computing channel bottom infiltration during a runoff event.

For example, suppose 3 ft of coarse material with an infiltration rate of 15 ft/day overlie a silt layer 1 ft thick. The coarse material has an initial water content of 15% by volume, and holds 25% water by volume at saturation. Assume the silt is initially saturated with water. The amount of water that can be added to this soil to reach saturation is therefore (0.25 to 0.15) x 3 ft = 0.3 ft. At 15 ft/day, this volume of water would infiltrate in 0.02 days, or about 29 min. If a runoff event lasting 4 hr with a water depth of 1 ft occurs, the coarse upper layer would saturate in about 29 min, after which a total pressure head of about 5 ft (1 ft of runoff depth + 3 ft of saturated coarse material + 1 ft of saturated silt) would exist across the silt layer. Because of the pressure head, drainage through the silt would occur at about five times the silt's infiltration rate. If the silt's infiltration rate is 1 cm/day, during the remaining 3 hr and 31 min of runoff, 0.73 cm (0.024 ft) of water could pass through the silt. Flow through the silt during the runoff event is about 8% of the change in water storage of the overlying coarse materials. Depth to silt layers, infiltration rates, channel widths, stormflow durations, etc. are inherently variable. With the relatively few measurements available, estimates of channel infiltration potential for a single event are probably ±100%. Consequently, the 8% of total flow through the silt during the runoff event is small enough to ignore.

Observations of coarse arroyo materials in the days following runoff events suggest that evaporation does not consume much of the water left behind by runoff events. Some moisture is evident to the eye or to touch throughout the year at depths of about 1 ft, and water content profiles suggest water contents at 3 ft are similar to those at depth throughout the year (Figure A-3). Therefore, the total amount of aquifer recharge occurring following a typical runoff event can be reasonably estimated if the volume of coarse textured materials above silt layers is known. With an infiltration rate of 15 ft/day (less than many measurements, Table A-4), a 4-hr runoff event can result in 2.5 ft of infiltration into coarse soils, which is adequate to bring 25 ft of those materials from a water content of 15% to 25%. At neutron access Tube NA-4 in Tijeras Arroyo, we have observed water movement at depths of 20 ft within 4 hr of the beginning of a 2-hr runoff event. However, this tube is installed in the only location known where silt layers appear to be absent from the surface to large depths (60 ft). Hand excavations during this arroyo survey failed to uncover silt layers at only 3 of 13 locations, and digging stopped at these 3 sites at an average depth of 6.6 ft. The relatively uniform, high infiltration rates of coarse materials generally are not limiting, while the silt layers are practically a barrier in the context of the period of active runoff. In the days following the runoff event, most of the water retarded by silt layers drains through the silt and becomes aquifer recharge. A smaller fraction evaporates from the surface or is extracted by plant roots from the edges of the channels. Ignoring water lost to evaporation helps to correct any underestimate of recharge caused by ignoring infiltration through silt during active runoff.

The volume of coarse materials over fines was estimated from arroyo survey data by the sum of channel surface areas as measured in the survey, i.e., length x (bankfull width - 2 ft) x depth to silt. Bankfull width was reduced by 2 ft because our observations have suggested that most flow events peak at elevations substantially lower than bankfull. The volume of water recharged per runoff event was calculated by multiplying the volume of coarse materials by 0.1. The factor 0.1 was a rough approximation of the amount that water contents would increase between average preflow conditions and immediate postflow conditions, based on visual observations of neutron data plots; this factor is believed to be conservative (i.e., larger than actual).

Data from two USGS stream gages on Arroyo del Coyote from 1989 to 1994 indicate that an average of about 3 distinctively separate runoff events occur each year. Multiplying this number of events by the volume of available (0.1 cm^3/cm^3) pore space above silt layers in this arroyo (Figure A-4) indicates total annual recharge through this arroyo bottom averages about 400,000 ft^3 annually. Similar computations for Tijeras Arroyo indicate about nine runoff events annually, for a total of about 2.2 million ft^3 of annual recharge. Note that this analysis assumes that every section of each arroyo has an equal number of runoff events. For example, the recharge estimate for Arroyo del Coyote is larger than the flow estimate made from measurements near Coyote Springs in 1995 (Table A-2), yet recharge could still have reached the annual average due to rainfall/runoff on portions of the watershed below Coyote Springs. The annual estimate obtained for Tijeras Arroyo in this manner is equal to 3.35 ft of recharge per square foot of channel surface as measured during arroyo survey work in 1995; this value is about 85% of the independent estimate made using the two neutron access tubes in Tijeras Arroyo that have underlying silt layers (Section A.6). Note that because the volume of available pore space (0.1 cm^3/cm^3) is conservative and because rainfall was above average (Section A.2) during most years the USGS gages were in operation, average annual aquifer recharge from these arroyos is probably somewhat lower (e.g., 20%) than these estimates.

These recharge estimates apply to Tijeras Arroyo and Arroyo del Coyote only. The third largest arroyo on the SNL/KAFB area begins in the vicinity of Mt. Washington and disappears in the southern part of TA-III. In 1994, a water sampler on this arroyo just inside TA-III was triggered by rising water and collected a full set of samples. Based on this and some discussion with other personnel, a stream gage and neutron access tube was installed within TA-III (stream gage #5, Figure A-1). During the installation of the neutron tube, soil water contents higher than any observed elsewhere were discovered, leading us to suspect that this channel was a major aquifer recharge source. This was believed to be an active streamflow site and therefore streamflow quantities, durations, and arroyo-channel infiltration were to be monitored. On five occasions during 1995, substantial rising water levels occurred at the stream gage; four of these rises peaked in excess of 1 ft above the channel bottom. Unlike other area streams, though, the water levels rose rapidly to a plateau, and fell slowly and linearly over a period of almost 24 hr. On one of these occasions, the site was observed during rising water and it was noted that small amounts of runoff from local roads were collecting in the channel. The channel was blocked by earthwork a short distance downstream, which caused the rise in water level; no flow was observed in the channel east of the TA-III boundary fence. It was concluded that small amounts of man-induced runoff from roads and other development enter this arroyo channel, pond behind an artificial channel blockage about 120 yd inside the TA-III boundary fence, and infiltrate the channel bottom causing some very localized aquifer recharge. The volume of recharge is on the order of several hundred to a few thousand cubic feet per event. Elimination of the channel blockage (both here and perhaps at additional points downstream) would eliminate most if not all of the recharge now occurring.

Subsequent investigations related to these events included excavations within the main arroyo channel about 500 yd east (upstream) of TA-III. Much caliche (the residue left behind by rainfall evaporation) was found within about 1 ft of the channel bottom within a well-channelized portion of the arroyo. The caliche indicates that natural arroyo flows are too infrequent, too small, and of too short duration to produce aquifer recharge in this area. Because this is the largest arroyo in this portion of KAFB, it is reasonable to assume that no significant or measurable natural recharge occurs from other arroyos in the area near TA-III. With the exception of two small infiltration tests, no hydrology work has been performed in the headwaters areas of southern KAFB arroyos. One principal reason is much of this area was an impact area for naval gun practice during World War II; significant quantities of unexploded ordnance may be present.

The shape of the principal surface watersheds on southern KAFB is different from that of Arroyo del Coyote. The Arroyo del Coyote watershed has a "light bulb" shape, while these watersheds are long rectangles. As a result, the ratio of the length of the main arroyo channel per unit area of watershed is larger here than in Arroyo del Coyote. This makes inherently less runoff available per foot of main channel length, which may partially explain why most arroyos in this region disappear before leaving SNL/KAFB. Flow measurements made in the Arroyo del Coyote basin show maximum runoff to be about 0.015 area in. (i.e., 0.015 in. over the entire watershed area). Because these channels appear to flow less frequently, potential recharge (streamflow) through the arroyo bottoms here is probably less than 0.015 area in.; our educated guess would be 0.005 area in. of potential recharge through arroyos on southern KAFB. Any arroyo recharge must be occurring near the mountains, because the caliche suggests there is none in western portions of the basin. If the estimated 0.005 area in. of arroyo recharge is applied to the portion of this basin from Explosive Ordnance Disposal (EOD) Hill east to the Manzano Lookout Tower and south to the KAFB boundary, it is equal to about 100,000 ft^3/yr. The SWHC Project does not plan to do any additional field work related to arroyo recharge estimation.

A.8 AQUIFER RECHARGE ESTIMATION BY ESTIMATION OF GROUNDWATER FLOW - SOUTHERN KIRTLAND AIR FORCE BASE AREA

Long-term aquifer recharge from surface soils at a point is equal to precipitation less surface runoff and evapotranspiration. Surface runoff in this area is typically, at most, a few tenths of one percent of rainfall (Section A.3). Aquifer recharge is probably of the same order of magnitude as surface runoff, while most precipitation is lost to evapotranspiration. Evapotranspiration is notoriously hard to estimate, particularly in arid areas. Therefore, trying to estimate recharge from evapotranspiration and surface runoff estimates is fraught with error. For example, suppose evapotranspiration consumes 99.5% of precipitation, surface runoff is 0.1%, and 0.4% is aquifer recharge. If the surface runoff is accurately measured, but evapotranspiration is underestimated by 10% of total precipitation, aquifer recharge would be estimated as 100 - (0.1 + 89.5) = 10.4% of precipitation. Because actual recharge was 0.4% of precipitation, the estimated recharge is 26 times the actual. In reality, an estimate of evapotranspiration made independently based on energy-balance considerations would probably have a greater error than the 10% suggested here.

Alternatively, recharge can be estimated from groundwater flow; at steady state, the flow passing a point in the aquifer must equal recharge upgradient of that point. In areas influenced by pumping, this technique may not work because such a system is not at steady state. Pumping has not markedly influenced aquifer heads in eastern portions of SNL/KAFB, so this technique may be applicable here. The principal problem in estimating groundwater flow (and hence recharge) in this area is that data for heads, hydraulic conductivity, and aquifer thickness are sparse. In spite of this, estimating groundwater flow was attempted.

Initially, data from three wells where aquifer tests had been performed were used in connection with the potentiometric surface map (Plate II). These wells were TSA-1, TRN-1, and SFR-3. Though

TSA-1 appears to be in a different aquifer system (Arroyo del Coyote), all three wells were completed in shallow bedrock and probably are representative of the range of characteristics to be expected in the area. The average hydraulic conductivity in the three wells was 0.7 ft/day, and was assumed to apply across the aquifer (SNL/NM 1993, Table 3.2.4.3 and Section 4.4.3.2). The aquifer thickness assumed for the TSA-1 well (120 ft) (SNL/NM 1993) was assumed to be that present across the aquifer (the actual aquifer thickness, continuity, and hydraulic conductivity are unknown). This thickness and hydraulic conductivity combine to provide an estimated transmissivity of about 85 ft^2/day. The discharge per foot of width of an aquifer is equal to the gradient (ft/ft) of the heads multiplied by the aquifer transmissivity. The gradient between the Manzanita Mountains and well TRN-1 is about 0.0066, so the discharge calculated with these data is equal to 0.566 ft^3/day/ft of width. Assuming this flow rate occurs in the aquifer from the vicinity of School House Well south to the southern border of KAFB (about 2.8 mi), the total flow is equal to about 3 million ft^3/yr.

Data for projecting flow across wide areas such as was just discussed are sparse. However, at the Inhalation Toxicology Research Institute (ITRI) facility, a shallow alluvial aquifer is present with a wealth of data. If the flows estimated (see above) become part of the alluvial system at ITRI, continuity (in a steady-state system) and concepts of groundwater streamlines require that the flows per unit width of the alluvial system at ITRI be equal to the flows entering that system. Previous reports indicated that the alluvial aquifer at ITRI is between 7 ft and 9 ft thick, averages 8.4 ft thick, and has an average hydraulic conductivity of 38.25 ft/day (SNL/NM 1993, Table 4-9, page 4-58). These values may be slightly out of date, but are adequate for the purposes here. Steep hydraulic gradients are apparent just to the east and west of ITRI, and recharge from ponds or septic tanks may have altered natural gradients here to some degree. One pair of wells suggest a westward gradient of about 0.0015 over a distance of about 1875 ft (Plate IV). Discharge through this aquifer with K_s = 38.25, depth = 8.4 ft, and a gradient of 0.0015 would be 0.49 ft^3/day/ft of width, very close to the 0.566 ft^3/day/ft estimated for other parts of the eastern aquifer.

The two independent estimates of aquifer flow rates are almost identical, a result that would not be expected given the quantity and quality of available data. However, we suspect (based on little more that the estimated aquifer flow (and hence aquifer recharge) in this area may be within $\pm 500\%$ of the 3 million ft^3/yr estimated here. This value represents our best (to date) estimate of total watershed recharge to the portion of the aquifer east of a line from EOD Hill or School House Well to the southern KAFB boundary; additional data or analysis may affect this estimate considerably. Arroyo recharge, mountain-top recharge, and mountain-front recharge are all included in this value. Given our estimate of (near mountain) arroyo recharge of 100,000 ft^3/yr (Section A.7), mountain-top recharge and mountain-front recharge appears to account for something in excess of 90% of total aquifer recharge occurring on southern KAFB. For perspective, total estimated annual recharge in this area is equal to water used by about 260 people at a use rate of 250 gal./person/day, or roughly 0.15 (watershed) area inches. West of this described line, we suspect recharge is nearly zero in the area south of Arroyo del Coyote except where water is artificially ponded, such as at blocked arroyo channels or septic tank drainfields. Such localized recharge may be significant to contaminant transport, but is inconsequential in terms of regional flow.

A.9 INFILTRATION TEST NEAR WELL MRN-1

An aquifer test was performed at the site of wells MRN-1 and MRN-2 September 19 to 21, 1995 (Figure A-1). This test involved pumping from the aquifer at a rate of approximately 25 gallons per minute (gpm) for 48 hr, with pumping halting at 8:30 a.m. on September 21. The total volume of water pumped was approximately 72,000 gal. The discharge of this quantity of water to the surface was taken as an opportunity to do a simple, large-scale infiltration test at low cost. In particular, the volume of water available was not greatly dissimilar to an historical discharge of reactor-coolant water (about 270,000 gal.) at the Mixed Waste Landfill. Objectives of the infiltration test were to determine the depth to which water would move following a large addition of water in a typical inter-arroyo area, and to help define the water content at which flows essentially cease. Our hypotheses were that the water would not move to great depths, and that the water content at which flow becomes zero is significantly higher than the ambient water content of these inter-arroyo soils. It was recognized that both of these answers may only be determined after a long period of time, but that the future level of effort would be small. For example, measuring the water at each foot of depth in a 45 ft neutron access tube is about a 1-hr job.

Prior to the beginning of the aquifer test, an earthen berm with a 10 in. height and a radius of 20.5 ft was installed around the discharge outlet. Three tubes for repetitive soil water measurements were installed to depths of 9.5 ft with a hand auger. One of these was in the plot center, and the other two were 10 ft and 15 ft, respectively, outside the wetted perimeter of the bermed ponding area. Enough caliche was present to make augering difficult during the tube installation. The ability of water to penetrate the caliche was unknown, so the center tube was grouted full length with dry, powdered bentonite clay. This rendered exact estimation of total water content impossible, but ensured that infiltrating water would not follow the auger hole to depth. The center tube could only be used to determine if water reached a depth of 9.5 ft or less. A fourth tube was installed 6 ft to the side of the center tube. The intention was to install this tube to a depth of 50 ft. However, a very hard layer was encountered that could not be penetrated with a hand auger. This tube was installed to a depth of 27.5 ft where the hard layer was encountered, and a pure bentonite seal was used on the upper 9 ft.

Finally, a short section of the same tubing material (2-in. diameter electrical conduit) was installed about 40 ft west of the center of the plot for calibration purposes. Two samples were cored from the (naturally dry) installation hole at depths of 23 to 36 in. and 26 to 29 in.; these samples had an average water content of 4.5% (4.5% and 4.51%, respectively). The tube was neutron logged for 256 sec at sensor depths of 24 in., 26 in., and 28 in., where the average "count" was 3392 (standard deviation 21.9 counts). Subsequently, a 14-in. diameter steel ring was driven into the soil with the neutron access tube in its center. Approximately 25 gal. of water were infiltrated within this ring, a process requiring about 24 hr. About 12 hr after infiltration ceased, six soil samples were obtained from three holes equally spaced and about 2.5 in. from the tube. These samples had an average water content of 18.96% (standard deviation 0.91%). Neutron logging at depths of 24 in., 26 in., and 28 in. (similar to the sampled depth) resulted in an average "count" of 8164 (standard deviation 41.7 counts). Using a typical, linear assumption for neutron moisture logging, these data resulted in a calibration curve for electrical conduit of:

$$\Theta = 3.03\text{E} - 3(\text{C}) - 5.77$$

where Θ is water content in % by volume, and C is number of counts measured by the neutron probe (with our CPN 503DR probe, "counts" are all standardized to a particular time interval, regardless of the length of the counting period).

Water breached the berm and escaped during the first night of pumping. Based on the area wetted and the depth of wetted soils, it is estimated that about 2500 gal. were lost from the principal infiltration area. Subsequently, a secondary berm was installed that added about 800 ft^2 to the infiltrating pond's original area of about 1320 ft^2. This addition resulted in one of the "outside" neutron tubes being within the ponded area, and the other within about 1.5 ft of the ponded water. These two tubes could no longer be used to estimate lateral spreading and were abandoned. With the additional ponding area, water remained ponded throughout the bermed area and was contained within it through the remaining 24 hr of the test. On the average, about 4.3 ft of water was added to the soil beneath the pond. The berm around the edges of the pond was breached in several locations to permit drainage soon after all ponded water from aquifer pumping had infiltrated.

By September 25, 1995 (4 days after pumping ceased), it was apparent that drainage would pass the bottom of the deepest (27.5 ft) neutron access tube (Figure A-5). On September 29, a trailer-mounted cone penetrometer was used to drive a tube to a total depth of 35 ft. At this depth, the penetrometer became stuck. During the process of retrieving it, intense rainfall occurred that resulted in water ponding around the stuck pipe. It is suspected that up to 200 gal. of water could have entered the ground through this hole. On October 6, a tube was installed to a total depth of approximately 45 ft by using a trailer-mounted hollow-stem auger rig to drill to 36 ft, then hand augering through the hollow stem to total depth. This drilling technique resulted in a hole diameter of approximately 6 in. at 36 ft, and 3.25 in. between 36 ft and 45 ft. The lower portion the annular space around the tube in this hole was backfilled using about 200 lb of sifted, dry, surface sands collected along the upper edges of a nearby pit. Materials augered from the hole were used to backfill the remaining space to within about 1.5 ft of the surface, and the top portion was packed with wet fine materials from surface soils that had formed the berm around the pond. The very top of the fill was mounded to prevent accumulation of standing water along the tube.

Water content data collected over time from before the test to about 7 weeks after pumping stopped are shown in Figure A-5(A). The water-content profiles shown in Figure A-5(A) represent composites of three separate tubes. Data from the central 9.5-ft tube, the 27.5-ft tube, and the 45-ft tube are shown for the upper 9.5 ft, 10 to 27 ft, and 28 to 45 ft, respectively. The deepest tube was bored with a much larger (6 in.) hole to 35 ft, so its readings were not believed to be as reliable for the upper depths. Field data showing that the shortest tube had been sealed full length with bentonite were temporarily misplaced, and for a time it was assumed that its data were better for the uppermost 9 ft. Therefore, much early data collection did not measure each tube, top to bottom, but only those elevations where the data were believed to be most representative.

Several conclusions can be drawn from Figure A-5(A). First, water had not reached below 42 ft after 4 weeks of drainage. Second, water had reached the maximum depth at which it could be measured with these tubes (45 ft) after 6 weeks of drainage. Third, the use of bentonite clay to seal the upper 8 to 10 ft of each of the shorter (9.5 ft and 27.5 ft), original tubes eliminates the possibility of doing mass balance calculations to track losses over time. Measured water contents in bentonite-sealed areas reflect the tremendous water holding capacity of the bentonite, rather than draining water in the surrounding soil. As water drains from upper layers to previously "dry," lower layers, the total apparent water volume of the profile increases because elevations effected by the bentonite maintain readings higher those in the draining soil surrounding the bentonite.

Because the 45-ft tube has no bentonite, data from it can be examined to estimate water balance, though limitations of this tube must be considered (6-in. upper hole diameter, mixed backfill in upper 35 ft). Data for the full length of this tube are available only for November 3, 1995. These data show 7.72 ft of water are present in the upper 45-ft profile, as compared to 8.02 ft for the profile created using bentonited tubes (Figure A-5[B]). At 5% by volume (roughly estimated from Figure A-5(A), the initial water content of the single-tube profile would be 2.25 ft. Therefore, while less than the water content is estimated by the combined tubes, this tube suggests an added water volume of about 5.5 ft, some

1.2 ft more than the volume we believe infiltrated. Therefore, the ability to do water balance computations is weak at best.

A new, deeper tube would be needed to determine the maximum depth reached by the percolating water because water has reached the bottom of the existing, 45-ft access tube. As is, the existing tubes may still be used to estimate the water content at which drainage ceases. This can be determined by absence of changing water contents at depth as determined by infrequent measurements. A value close to residual water content may be available from such measurements in a few years.

A.10 CONCLUSIONS

We have determined that 70,000 gal. of water applied to an approximately 2100 ft^2 area penetrated to a depth of 45 ft in 6 weeks. We suspect that this water will eventually reach a depth in excess of 55 to 60 ft. The maximum depth to which applied water will penetrate at a given site is a function of (1) the volume of water applied, (2) the surface area to which it is applied, (3) the degree to which the water spreads laterally, and (4) the amount of additional water the soil can hold while maintaining zero drainage. All else being equal, larger volumes of water will penetrate to greater depths, though the maximum depth will not double with twice the water volume. Application of the water to a smaller surface area will increase penetration depth. At one extreme, an infinitely large area of application reduces penetration to zero. The other extreme, application of water at a single point, will not result in infinite penetration because of lateral spreading of the wetting front. The degree of lateral spreading has a major effect on the depth of penetration. If the wetted profile is cone shaped, the volume of wetted soil increases with the cube of the depth; doubling the depth penetrated from a point source results in 8 times the wetted soil volume. From a point source on the surface, a cone with lateral spreading in all directions equal to the depth penetrated produces 8378 ft^3 of wetted soil in the first 20 ft of penetration; if this lateral spreading is equal to 1/2 the depth penetrated, only 2094 ft^3 of soil will be wetted in the top 20 ft. Finally, the ultimate depth penetrated by the water is controlled by the additional capacity of the soil to hold water; this concept is based on the assumption that below some residual water content, no drainage occurs from the soil. Theoretically, if the soil is exactly at its residual water content, a single additional drop of water would result in some flow out of the soil profile if no other losses of water (e.g., evaporation) occur; with a 500-ft deep soil profile, this could take millions of years.

Determining exactly what water content constitutes the residual, no flow amount is problematic. However, using commonly available techniques (e.g., the van Genuchten/Muelem methods), most measurements made locally suggest the water contents of natural, inter-arroyo soils are well below this residual value. While the accuracy of the absolute value of the estimated residual water contents is unclear, we do not doubt that the natural water contents of inter-arroyo soils are less than their residual water contents. Therefore, these soils have some capacity to store additional water indefinitely.

Given some storage capacity in the soil, the principal, unknown factor that will determine the ultimate depth of movement of a finite volume of water that percolates to below the zone influenced by evapotranspiration will be the degree of lateral spreading that occurs. This is controlled by what is known as the anisotropy of the soil.

A.11 REFERENCES

Fritts, J. E., 1994. Tijeras Arroyo Neutron Access Tube Installation Project, Internal memo to Ross Wolford, Environmental Restoration Project, July 20, SNL/NM ER Records Center file ER/1330/SUW/LOG, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Kautsky, M., R. A. Wolford, and W. S. McKenna, 1995. Field and laboratory data collection of potential infiltration rates. Poster H41B-6 presented at 1995 fall meeting of the American Geophysical Union (AGU), San Francisco, CA, December, 1995; abstract published in AGU-EOS fall meeting supplement, Nov. 7, 1995.

Morris, H. M. and J. M. Wiggert, 1972. Applied Hydraulics in Engineering, 2nd Ed., Ronald Press, NY, page 133.

NOAA, 1917-1995. National Oceanic and Atmospheric Administration. Local Climatological Data for New Mexico - Annual Summaries With Comparative Data (separate document for each year), National Weather Service, Albuquerque, New Mexico and personal communication, December 1995.

Rust Geotech, 1995. Characterization of arroyo infiltration properties at Sandia National Laboratories/New Mexico and Kirtland Air Force Base. Report submitted to US DOE, Albuquerque Operations Office and Grand Junction Projects Office, Grand Junction, CO, under DOE contract No. DE-AC04-94AL96907, October, 1995.

SNL/NM, 1991. Sandia National Laboratories/New Mexico. Groundwater Monitoring Program Calendar Year 1990 Annual Report. Sandia National Laboratories/New Mexico, Albuquerque, NM, March 1, 1991.

SNL/NM, 1993. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1992 Annual Report. SAND93-0681, Environmental Restoration Program, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994. Site-Wide Hydrogeologic Characterization Project Calendar Year 1993, Annual Report. Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1995. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project Calendar Year 1994 Annual Report. Environmental Restoration Program, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Waltemeyer, S. D., 1986. Techniques for Estimating Flood-Flow Frequency for Unregulated Streams in New Mexico, USGS Water-Resources Investigations Report 86-4104, Albuquerque, NM.

APPENDIX B
VADOSE ZONE HYDROLOGY ACTIVITIES

Point of Contact: James T. McCord (SNL/NM)

Authors: James R. Brainard (SNL/NM)
Peter W. Burck (INTERA Inc.)
Robert J. Glass (SNL/NM)
James T. McCord (SNL/NM)

CONTENTS

TABLES

B.1 INTRODUCTION

This appendix summarizes the vadose zone hydrology activities performed in 1995. Section B.2 discusses the Tijeras Arroyo Infiltration Study (see Attachment 3, also), and Section B.3 presents the results of several environmental tracer tests. The Site-Wide Hydrogeologic Characterization (SWHC) Project surface-water group performed an interarroyo infiltration test near Well MRN-1, the results of which are summarized in Appendix A.9.

B.2 TIJERAS ARROYO INFILTRATION EXPERIMENT

Sandia National Laboratories/New Mexico (SNL/NM) conducted a water infiltration study on Kirtland Air Force Base (KAFB) in support of the SWHC Project. This study is referred to as the Tijeras Arroyo Infiltration Experiment (TAIE). Nearly all potential groundwater contamination at SNL/NM Environmental Restoration (ER) sites originates from near-surface sources, with large-volume liquid discharges (both inadvertent spills and intentional effluent injections) providing the most likely sources of saturated zone contamination. Furthermore, recharge through the vadose zone from local ephemeral stream channels such as Tijeras Arroyo and Arroyo del Coyote may be significant in terms of influencing local groundwater flow. This section briefly summarizes an infiltration test designed to explore the hydraulic response of the vadose zone to a transient near-surface ponding event, providing a solid foundation for assessing actual ER sites and predicting their impact on human health and the environment. More detailed information on this infiltration test can be found in Attachment 3.

Site restoration plans are often supported by numerical studies of flow and transport at contaminated sites. In recent years, advances in the computational and analytical methods used to solve vadose zone flow and transport problems have provided the researcher with powerful predictive tools. However, numerical predictions are fraught with considerable uncertainties. These uncertainties result in part from the assumptions made in the particular model being used and in part from errors made in obtaining the hydrologic properties and assumptions made about the spatial distributions of these properties. Confidence and validation of predictions are also often limited by the lack of field data. This is especially true in arid regions where vadose zones are commonly greater than 100 m thick and are comprised of very heterogeneous geologic deposits. Difficulties arise both in collecting representative samples and obtaining the necessary hydraulic properties from laboratory samples. In situ hydraulic data are attractive alternatives to data from samples; however, obtaining meaningful in situ data tends to be time-consuming and expensive. Additionally, disturbed and undisturbed samples taken from field sites can be subjected to a variety of laboratory measurements for quantification of hydraulic properties. The complexity of the various laboratory techniques ranges from simple (e.g., grain size analyses) to quite involved (one-step outflow experiments), and thus costs vary considerably. No solid data exist to assess the reliability of the in situ and laboratory techniques, and a comparative study in which all techniques are applied at a single infiltration test site can provide a basis for such an assessment.

A highly instrumented large-scale infiltration test was conducted at SNL/NM to provide data that can be used as a foundation for reliable numerical predictions. During the infiltration test, the natural hydrologic system was perturbed by water ponded on the ground surface, and the subsurface response was monitored by arrays of instruments that provided the necessary hydrologic data for comparative numerical studies. Hydrologic properties were obtained through a variety of field and laboratory measurements. Numerical studies will attempt to simulate hydraulic flow behavior observed in the large scale infiltration event, incorporating both in situ and laboratory data. Results of these simulations can provide guidance to the ER Project concerning which property measurement techniques are most appropriate for hydrologic characterization at other sites with similar vadose zone materials across the SNL/KAFB region. The results will also lend insight as to which modeling techniques (e.g., simple homogeneous or complex heterogeneous numerical) are most suitable for a variety of ER site characterization and site assessment scenarios.

This infiltration test was conducted in a heterogeneous alluvial fan deposit. The overall goal of this infiltration test was to provide a comprehensive and high-quality hydrologic data set that can be used to investigate vadose zone flow and contaminant transport processes. This project was undertaken by personnel from the SWHC Project (SNL/NM Department 7584), the Environment Center (SNL/NM Department 6624), and the Geohydrology Department (SNL/NM Department 6115). Site preparation for the infiltration test began in May 1995 and infiltration lasted 27 days (from November 7 to December 4, 1995). The Geohydrology Department (SNL/NM Department 6115) is continuing to monitor the site.

B.2.1 Project Objectives

The infiltration test supports SNL/NM ER Project efforts to assess potential vadose zone contamination sites. Objectives included the following:

1. Obtain information (infiltration rates, wetting front advance rates, moisture content, and pressure fields) that can be used to elucidate flow processes in heterogeneous unsaturated geologic deposits present at SNL/NM ER sites.

2. Provide in situ hydraulic property data for comparison to data obtained from a variety of laboratory analyses of samples collected from the site.

3. Use the results of the experiment to develop guidelines for ER site project leaders for characterization and assessment of vadose zone problems.

B.2.2 Project Description

The TAIE was located on a ridge extending from the north escarpment of Tijeras Arroyo located south of Technical Area IV (TA-IV) and northeast of Pennsylvania Boulevard.

B.2.2.1 Site preparation and water application

The infiltration test involved infiltrating potable water into naturally occurring geologic deposits representative of other deposits found at depth within KAFB. Surficial deposits of silts, sands, and gravels were removed to provide a flat infiltration surface comprised of finer grained materials (silts).

A 2-m-diameter infiltrometer ring was installed on the excavated surface. Water was supplied to the ring and maintained at a constant water level during the test. Approximately 6300 gal. of water were applied to the ground surface during the test.

Water for the test was obtained from potable supplies within KAFB and was transported to the site in a high-density polyethylene container designed to fit in the bed of a pickup truck. Infiltration rates were monitored by in-line flow meters and pressure transducers in the supply tanks.

B.2.2.2 Subsurface monitoring instrumentation

The response of the geologic media to the infiltration test was monitored with a variety of equipment. Arrays of Time Domain Reflectometry (TDR) moisture probes and tensiometers (incorporating pressure transducers) were used to determine water content and pressure potentials, respectively. These instruments were installed to encircle the infiltrometer and were located at various depths to 4 m below ground surface (bgs). Neutron moisture probes were used to monitor the wetting front advance and moisture contents at the center of the infiltrometer and at locations outside the infiltrometer. Thermocouples, installed with the TDR probes, were used to monitor temperature changes from the infiltrating water. The installation of this equipment was accomplished using a variety of techniques including by hand, a truck-mounted geoprobe, and a Big Beaver drill rig to auger the necessary holes. The arrays of TDR probes, tensiometers, and thermocouples were monitored with multiplexed computers and dataloggers. Power for the data acquisition systems was supplied by a low-voltage photovoltaic system. A weather station was installed nearby to monitor parameters such as ambient air temperature, relative humidity, barometric pressure, and precipitation.

B.2.2.3 Pretest subsurface sampling and characterization

A backhoe was used to excavate the surficial deposits and five benched trenches adjacent to the test site. The trenches allowed direct observation of geologic features adjacent to the infiltration site and provided sites for studies incorporating tension infiltrometers and air permeameters. Benching of the trenches provided level surfaces for the tension infiltrometer and allowed access to subsurface deposits without exceeding the maximum vertical wall depth allowed by the Occupational Safety and Health Administration (OSHA) for nonconfined spaces. Soil samples were collected from the trenches, as well as during instrument installation at the site. Moisture characteristic, hydraulic conductivity, bulk density, and grain size distribution data were obtained from the samples.

B.2.2.4 Infiltration sequence

Water was allowed to infiltrate until a bulb of sufficient volume was present to allow the instrument arrays to capture the continued spreading of the bulb. Once infiltration was stopped, moisture contents and pressure potentials changed as the bulb continued to expand.

B.2.3 Results

The results of the TAIE are presented in Attachment 3 of this report.

B.3 ENVIRONMENTAL TRACER STUDIES

For most ER sites across SNL/KAFB, groundwater recharge (deep percolation of water toward the water table) provides the primary mechanism for downward transport of solutes. To characterize representative rates of downward migration of potential contaminants on SNL/KAFB, environmental tracers of natural recharge are employed. Environmental tracers provide one of the most robust approaches toward quantification of natural groundwater recharge rates in arid and semiarid rangelands (Gee and Hillel 1988, Allison et al. 1994). Three different environmental tracer investigations were undertaken by the SWHC Project in 1995. The first approach utilized chloride analyses of soil-water extracts from samples obtained from the geologic trenches at the TAIE site to estimate natural recharge rates in representative vadose zone hydrogeologic settings across the study area. The two other studies assessed the reliability of the tracer approaches at the SNL/NM site: the first looked at the impact of spatially variable water movement on tracer recharge estimates, and the second considered the potential impact of fine-grained layers on recharge estimates.

B.3.1 Relevance to the Environmental Restoration Project

The vadose zone, which links the surface-water hydrology and the groundwater hydrology, is an important part of the hydrologic system in the SNL/KAFB area. As described in Section 3.2.3 of this report, the vadose zone thickness is generally large (from 15 to >150 m); consequently, most contaminants released near the ground surface must travel a long distance before reaching the water table. The majority of the ER sites are located at or near the land surface. The types of sites SNL/NM is responsible for characterizing (and possibly remediating) include landfills, underground storage tanks, septic tank drainage fields, surface dump sites, localized surface spills, and areas with scattered debris from firing range tests. Most of these sites experience movement of contaminants into the subsurface under ambient fluxes, whereas others involve concentrated effluent loading. This study is applicable to sites with transport under ambient fluxes. The 1993 annual report (SNL/NM 1994a, Section 5.8) included an analysis of solute transport under ambient fluxes that showed the groundwater recharge rate to be one of the two most important parameters controlling movement of contaminants toward the water table.

B.3.2 Environmental Tracers of Recharge Through the Vadose Zone

In general, environmental tracers can be defined as readily identifiable constituents of atmospheric precipitation that move through geological media along with the percolating water. These constituents can either be part of the water molecules themselves (such as isotopes of hydrogen and oxygen) or they may be highly soluble, nonreactive solutes (such as chloride). Such constituents are referred to as environmental tracers because they are naturally occurring and because some near-surface process (either natural or anthropogenic) induces some quantifiable characteristic signature in the water. This characteristic signature effectively labels the water, and the label either remains unchanged or changes predictably as that parcel of water passes through the subsurface environment. Assuming that (1) the tracer is uniformly applied in space on a stable geologic surface at the field scale, (2) one-dimensional vertical downward flow predominates, and (3) the tracer moves along conservatively with percolating groundwater, a variety of models have been developed to quantify groundwater recharge rates through the unsaturated zone based on environmental tracer concentration versus depth profiles.

Many feel that environmental tracers provide the best tool for estimating recharge rates (e.g., Gee and Hillel 1988, Phillips 1994, Allison et al. 1994). Thus these tracers, in particular the chloride mass balance approach, were used for quantifying recharge across the entire SNL/KAFB area. To ensure measurement locations would provide recharge data representative of the range expected across the site, sites were selected based on their vadose zone hydrogeologic setting as defined by Parsons et al. (1994). Results of determination of recharge values at representative sites across SNL/KAFB are described in Section B.3.3.

Despite the broad consensus regarding the robust nature of tracer-based recharge estimates, some recent studies imply that care should be taken when interpreting tracer profiles. Previous work conducted as part of the SWHC Project (SNL/NM 1994a, McCord et al. 1996) has suggested that spatially variable water movement may violate assumption (2) above such that traditional techniques for interpreting tracer profiles may lead to errors in estimates of recharge rates. Section B.3.4 below describes a field investigation designed to assess the impacts of spatially variable water movement at a site representative of the SNL/KAFB region. In addition to concerns regarding the impact of spatially variable flow, recent work by Ankeny et al. (1996) raises the issue that anion exclusion/reverse osmosis may affect the movement of anionic tracers such as chloride, causing violations to assumption (3) above. Analysis of anion profiles from core collected at South Fence Road (SFR) appears to support Ankeny et al.'s (1996) concerns; this work is described in Section B.3.5. While the investigations described in Sections B.3.4 and B.3.5 do support the assertion that assumption-violating processes can affect recharge estimates, the magnitude of the estimation errors are small enough to render such recharge estimates within a factor of two or three of the actual value.

B.3.3 Estimation of Recharge Across Sandia National Laboratories/Kirtland Air Force Base Using the Chloride Mass Balance Method

Environmental tracers have been widely used to estimate average rates of natural groundwater recharge through thick unsaturated zones at the landscape scale (see review report by Allison et al. 1994). The two broad classes of tracers typically applied are bomb pulse and constant source tracers. In this study a constant-source anionic tracer, chloride, within a mass balance model is employed to quantify recharge.

The Chloride Mass Balance approach

Chloride is a naturally occurring solute in all precipitation. Its sources in the atmosphere are presumed to be oceanic aerosols (sea spray) and eolian deflation of chloride-bearing sedimentary deposits (Stone 1984). Chloride is thus continuously added to soil profiles as fallout in meteoric waters; it then moves downward through the soil dissolved in percolating water. In the near-surface shallow soils, most water is removed from the system by evaporation and transpiration, but the chloride is relatively unaffected by these processes. Thus, in general, the chloride ion concentration of the soil water should increase with depth throughout the evapotranspiration zone. Below the depth of plant rooting, the influence of the evaporation and transpiration processes should become increasingly negligible and chloride concentrations should approach some relatively constant value as shown in Figure B-1.

Assuming one-dimensional vertical flow, the average recharge rate at a given location could be determined using mass balance considerations:

$$R_{cl} = P\frac{C_p}{C_{sw}} \tag{1}$$

where

R_{cl} = the annual recharge rate (Darcy flux below the root zone) estimated by the chloride mass balance,
C_{sw} = the average chloride concentration of the soil water below the rooting depth,
C_p = the average chloride concentration in the precipitation at the site, and
P = the average annual precipitation rate at the site.

This approach has been applied in numerous recharge studies (see Phillips 1994 and Allison et al. 1994 for recent reviews of the approach and its application).

Selection of representative sites across Sandia National Laboratories/Kirtland Air Force Base

The SWHC Project is not charged with characterization with any particular site(s) across SNL/KAFB. To the contrary, the SWHC Project mission is to develop a site-wide hydrogeologic framework to provide context for the site-specific characterization efforts undertaken by the ER Project. Toward development of a regional framework, one of the first activities performed by the vadose zone subtask was the identification and definition of representative vadose zone settings (Parsons et al. 1994; SNL/NM 1994a). This task was undertaken using the ER Project's computerized Geographic Information System (GIS) as a tool for integrating and classifying data available for the entire site; data considered included permeability and storage capacity of surficial deposits, depth to the water table, elevation, and vegetation. Based on this effort, Parsons et al. (1994) defined a total of nine representative vadose zone hydrogeologic settings for the SNL/KAFB site. Table B-1 summarizes the settings and provides a brief description of the characteristics for each setting, while Figure B-2 provides a map showing the areal coverage of each vadose zone setting. The report by Parsons et al. (1994) includes a summary listing of the number of ER sites within each setting, and that listing is also included here in Table B-1. Through the identification of representative vadose zone settings, a basis was developed for transferring results obtained at sampled locations to unsampled sites.

Table B-1. Environmental Restoration Sites in Vadose Zone Hydrogeologic Settings

Setting	Description	Number of ER Sites[a]
ArCa	Arroyo and canyon vegetation, low to high slope.	17
RO	Rock outcrop, medium to high slope.	13
GHpMawc	Grassland, low to medium slope, high permeability, medium AWC.	44
GHpLawc	Grassland, low to medium slope, high permeability, low AWC.	18
GMp	Grassland, low to medium slope, medium permeability, low to high AWC.	53
WHpLawc	Open to closed canopy woodlands, low to medium slope, high permeability, low AWC.	18
WMp	Open to closed canopy woodlands, low to medium slope, medium permeability, low to high AWC.	13
WLpHawc	Closed canopy woodlands with low to medium slope, open to closed canopy woodlands with high slope, low permeability, high AWC.	0
WHs	Open to closed canopy woodlands, high slope, medium permeability, low to medium AWC.	8

[a] The total number of ER sites was 171 as of May 1993. Because many of the sites have more than one location, but the same site number at each location, there are more than 171 "sites" shown here.

Some of the nine identified vadose zone settings were excluded from our efforts to estimate recharge. Table B-1 shows that one of the nine settings (WLpHawc) contains no ER sites; thus no attempts were made to quantify recharge within that setting. One of the other settings (ArCa, arroyos and canyons) was eliminated because the surface-water subtask of the SWHC Project included efforts at characterization of seepage losses from such locations. Finally, the RO (rock outcrop) and WHs (woodland, high slope) settings were dropped because the three primary assumptions underlying the environmental tracer approach probably are significantly violated within these settings. Obtaining samples in these settings would be quite difficult anyway. That leaves five settings for which recharge estimates were obtained: GMp, GHpLawc, GHpMawc, WMp, and WHpLawc. Assuming that the arroyo recharge estimation is covered by the surface-water subtask, the recharge estimates presented below are representative of nearly 90% of the ER sites on SNL/KAFB.

Methodology and results

To quantify recharge across the SWHC Project study area, the chloride mass balance approach was employed. At least three samples from below the root zone were obtained in each of the selected vadose settings, and the soil-water chloride concentration for these samples was measured and input to equation (1) to obtain the recharge estimate.

Sample acquisition approaches varied across the site. For the GMp (grassland, medium permeability) and GHpLawc (grassland, high permeability, low available water capacity) settings, dozens of samples below the root zone were obtained as part of detailed recharge studies undertaken for the Mixed Waste Landfill (MWL), the Chemical Waste Landfill (CWL), and the SFR project. For GHpMawc (grassland, high permeability, medium available water capacity), many samples were obtained below the root zone for the Tijeras Arroyo infiltration test described earlier in this appendix. For the other two settings investigated, WMp (pinion-juniper woodland, medium permeability) and WHpLawc (woodland, high permeability, low available water capacity), samples taken from the bottom of some of the geology soil pits were used for chloride analysis (Attachment 1, Appendix D).

Samples obtained in the field were prepared for chloride analysis as follows. After oven drying, 100 g of soil were mixed with 100 ml of distilled deionized water, and the resulting mixture was shaken overnight. After agitation, the samples were set aside long enough for the majority of the solids to settle out before removal of 10 ml of liquid from the top of the sample jar. The decant was analyzed for chloride concentration by ion chromotography. These measured concentrations were adjusted to in situ chloride concentration (in soil water) by correcting for initial moisture content of the soil.

The recharge estimate could then be obtained using in situ concentration in equation (1). The annual precipitation rate and precipitation chloride concentration used in (1) were P = 20 cm/yr and C_P = 0.35 mg/l, respectively. These values represent the precipitation rate for Albuquerque and the chloride concentration in precipitation for the Socorro area (70 miles south of Albuquerque) reported by Phillips (1994). Recharge estimates for the vadose zone hydrologeologic settings are summarized in Table B-2.

Table B-2. Chloride Mass Balance Estimated Recharge Rates for Tested Vadose Zone Settings

Vadose Zone Setting ID	Range of Estimated Recharge Rate (cm/yr)
GHpMawc	0.0029 - 0.0068
GMp and GHp Lawc	0.04 - 0.26
WHpLawc	0.015 - 0.07
WMp	0.018 - 0.03

Discussion of results

The results presented in Table B-2 show that recharge rates across the site are generally quite low, ranging between 0.01 and 0.26 cm/yr. Recalling the risk-based solute transport study summarized in the 1993 annual report (SNL/NM 1994a), recharge rates across the study area are generally smaller than the 1 cm/yr reported to be of concern for causing significantly deep invasion of potential contaminants.

B.3.4 Recharge Spatial Variability Study

As discussed previously, spatially variable water movement in the vadose zone may lead to significant violations in one-dimensional vertical flow assumption underlying the application of equation (1) for quantification of recharge rates. This issue was investigated in detail through numerical modeling (see SNL/NM 1994a and McCord et al. 1996). That modeling study showed that environmental tracer profiles could be strongly impacted by spatial variability, to the point that constant source tracer profiles could show significant recharge underestimation biases. The modeling study also showed that the underestimation biases could be accounted for in the field if sampling is handled at several locations and the locations are closely spaced. Based on those results, it was imperative to provide site-specific field data to assess the impacts of spatially variable water flow for the SNL/KAFB region. This section describes such a field study.

Methodology

A site just north of the CWL, as shown in Figure B-3, was selected for this study. This site was selected for two reasons: (1) the CWL ER Project needed to conduct a field recharge study as part of their site-specific compliance activities, and (2) the CWL lay within the vadose zone hydrogeologic setting, GMp (grassland, medium permeability), which contains more ER sites than any other setting (see Table B-1).

The CWL is located in the southeast corner of Technical Area III (TA-III) and is approximately 1.9 ac in areal extent. The sampling objectives are to determine the rates of groundwater recharge and vapor transport to the aquifer below the CWL and to assess sensitivity/spatial variability as affected by geologic heterogeneity. To fulfill these objectives, soil samples were collected from the soil boring locations shown in Figure B-3 using the Geoprobe. Geoprobe sampling allows collection of samples from depth with minimal evaporation of soil water.

A variety of physical and chemical parameters were measured in this study including bromide, chloride, tritium, moisture content, and particle size distribution (by sieving). All samples were analyzed by standard methods. Particle size distributions were determined via sieving down to a #200 screen. Volumetric water content was measured following the guidelines outlined in SNL/NM Field Operating Procedure 94-62, *Bulk Density, Porosity, and Moisture Content of Soils* (SNL/NM 1994b). Bromide and chloride concentrations were determined from soil water extracts using ion chromotography. Tritium results, to be obtained using liquid scintillation counting, were not available at the time of this report.

The boring locations are shown on Figures B-3 and B-4. The borings were drilled in the vicinity of monitoring well MW-6. The area near MW-6 was selected because soil sampling performed during the installation of MW-6 revealed no constituents of concern. Consequently, the borings were located outside areas of known or suspected contamination.

Of the 25 borings shown in Figure B-4, 13 of the sample locations (marked SV sampling locations in Figure B-4) were used for assessing spatial variability in the subsurface distribution of chloride, bromide, and tritium, and the other 12 (designated as I boreholes in Figure B-4) were completed in the first phase of this work, which was undertaken as part of the regulatory compliance activities for the CWL ER Project.

The samples obtained from the 13 SV boreholes (Figure B-4) were taken as 1-ft-long samples from continuous core acquired by the Geoprobe; these 1-ft-long samples were containerized individually. These shallow samples were subsequently analyzed for bromide, chloride, and tritium, as well as water content and particle size distribution. The bottom 15 ft (from 15 to 30 ft in depth bgs) were sampled in continuous 1.5-ft-long depth intervals and containerized individually. The deeper samples were subsequently analyzed for bromide and chloride (no tritium), as well as water content and particle size distribution. In the field, a Geoprobe sampler measuring 4 ft long with a 1.5-in. inside diameter was used. The inside of the sampler was lined with a 4-ft-long acetate liner. The liner was capped as soon as it is retrieved. Upon sample acquisition, the lithologic features of the soil were described.

Results

The chloride profiles observed at the site exhibit amazing uniformity in vertical transport of tracer from location to location, which is not surprising considering the uniformity of the geologic layering mapped in the trench. Detailed geologic mapping reveals layers that are essentially continuous from one end of the trench to the other. Plots of the depth versus moisture content and depth versus chloride for all data are presented in Figures B-5 and B-6, which show the mean profile along with the highest and lowest values at each depth. For all 13 profiles, the average concentration from the bottom four samples of each sampling location was used as input to equation (1) to compute recharge for that location. Figure B-7 shows the histogram of recharge estimates from all 17 locations. This histogram graphically demonstrates a uniformity in recharge that is consistent with the uniform layering.

Four conclusions can be drawn from these results.

- At the site just north of the CWL, the length scale of the geologic layering in the top 20 ft (6 m) of the profile is greater than the entire trench length of 32 ft (10 m). It is presumed that this profile is representative of vadose zone hydrogeologic setting GMp, which underlies more than 50 of the SNL/NM ER sites.

- Environmental tracer profiles, collected to a 20-ft depth at several boreholes located along the length of the trench, show remarkable uniformity. This result suggests that vadose zone transport exhibits primarily one-dimensional vertical flow at this scale.

  Based on the chloride profiles, recharge within the vadose zone hydrogeologic setting is computed to range between 6×10^{-2} cm/yr and 2.8×10^{-1} cm/yr. For volumetric moisture contents varying between 6% and 12%, this translates to seepage velocities ranging between 0.7 and 3.0 cm/yr.

- These estimates of recharge rates and seepage velocities are generally below the threshold value of 2 cm/yr identified in the 1993 annual report (SNL/NM 1994a), which represents the velocity at which potential contaminants are likely to have moved deeper than 8 m (20 ft) into the soil profile over the duration of SNL/NM activities.

B.3.5 Impact of Reverse Osmosis on Recharge Estimation Using Chloride Profiles

As discussed by Ankeny et al. (1996), reverse osmosis is a process that may result in differential velocities between chloride and water, inconsistent with the assumption that chloride behaves as a conservative tracer. While reverse osmosis has been confirmed to be an important process in compacted clays where electrical double layers with individual clay surfaces overlap, it has previously been neglected in the vadose zone. Ankeny et al. (1996) hypothesized that in vadose zone situations with very thin water films, the thickness of the electrical double layer may equal that of the total water film thickness; consequently, anions would be excluded from such water. This process is also called anion exclusion. This may be the cause of some of the chloride bulges described in the literature; the chloride would tend to build up in soils overlying geologic horizons with very thin water films. The net result with respect to recharge is that significant underestimation may occur if chloride bulges are attributed to different processes.

A prerequisite of reverse osmosis is the presence of an unsaturated, high specific surface area layer (e.g., a clayey layer). Such layers are the most likely to have water films thin enough to exclude anions. The effective water film thickness, L_w, can be estimated as:

$$L_w = \theta / A_s \tag{2}$$

where

θ = the volumetric water content $[L^3/L^3]$ and
A_s = the specific surface area $[L^2/L^3]$.

Ankeny et al. (1996) further hypothesized that if reverse osmosis does occur, then its magnitude will vary from anion to anion, depending on the charge density of the anion (proportional to valence divided by hydrated radius). This result suggested a potential diagnostic tool for identifying the occurrence of reverse osmosis: analysis of profiles for multiple anions and then comparing the ratio of the anionic concentrations. This approach would determine whether profiles for different anions exhibit identical or different behavior. If the anionic ratio remains constant with depth, reverse osmosis is not occurring. Thus two pieces of data are necessary to demonstrate the occurrence of reverse osmosis: (1) depth profiles of water film thickness (see equation 2) to measure volumetric moisture content and specific surface area and (2) depth profiles for multiple anions. If these profiles show a significant swing in the anion ratio at the same depth as very low water film thickness, then reverse osmosis can be inferred.

<u>**Methods and Results**</u>

To test this hypothesis, core samples were analyzed from a site on SNL/KAFB for which detailed sampling had already occurred. The core was taken from the SFR-1D borehole, for which essentially continuos core from the ground surface to a depth of 100 ft was available. In addition to the core, a continuous neutron log of the borehole was taken immediately after drilling. This neutron log could be used to compute the θ (volumetric moisture content) profile. Figure B-8 shows the moisture content versus depth profile.

Following visual inspection of the complete core, several zones were selected from which samples were obtained. These zones were selected because of the presence of fine-grained materials. The samples were subjected to laboratory analysis for specific surface area, as well as analysis for soil water chloride and bromide concentrations.

The specific surface area relevant to anion exclusion is that surface area on the external surfaces of the soil particles. All samples were subjected to a water adsorption method developed by Karathanasis and Hajek (1982). In addition the BET method (Brunauer et al. 1938) was employed on five of the samples. The water adsorption method measures both internal and external surface area, whereas the BET method measures external surface area only. On the five samples submitted to both methods, the external area ranged between 24% and 46% of the total (internal and external) surface area. Based on this result, the assumed external surface area was 33% of the total surface area on samples subjected to only the water adsorption method. This assumption is consistent with semiquantitative x-ray diffraction (XRD) mineralogical analysis of the clay composition, as well as with internal/external surface areas of clay minerals reported in the literature (Orchiston 1954). Volumetric external surface area results are plotted versus depth in Figure B-9, which shows a high surface area, clay-rich zone at approximately an 11-m depth.

For determination of anion concentrations in soil water, a soil-water extract was prepared by mixing 100 g of dry soil with 100 ml of distilled, deionized water. The samples were then shaken to ensure equilibration of the dissolved ion concentrations in the soil-water mixture. The extract solutions were then vacuum-filtered to remove all solids, and the filtered solutions were analyzed for both chloride and bromide concentrations using a Dionex ion chromatograph with a suppressor column and a conductivity detector. Depth profiles of the chloride and chloride to bromide ratios are plotted in Figures B-10 and B-11.

Discussion of Results

Viewing Figures B-8 through B-11 shows the results of this study. Note the high moisture content and high surface area horizon at roughly an 11.5-m depth that is internally consistent. (Finer, high surface area materials would tend to retain more moisture.) Also at the 11.5-m depth, a large chloride bulge as well as a jump in the chloride to bromide ratio can be seen. This observation is consistent with the presence of anion exclusion: the anions are being filtered, as evidenced by the chloride buildup, and the jump in the anionic ratio suggests differential filtration by the high surface area layer (due to the slightly higher charge density of bromide as compared to chloride). The background chloride to bromide ratio is roughly 50:1 to 90:1, as evidenced by measurements from precipitation collected in New Mexico (Dr. Rob Bowman, personal communication). If anion exclusion/reverse osmosis is the cause of the step change in the anionic ratio, then the presumption that the anions are not behaving as ideal tracers of water percolation at that horizon is reasonable.

The water velocity (~recharge rate) would be significantly underestimated if the anion concentration at the chloride bulge is used. Therefore, when applying equation (1) to estimate recharge, the higher anion concentrations (bulges) in the vicinity of the high surface area layer should be neglected. To more defensibly estimate recharge, the chloride concentration from below the root zone but above the depth of the jump in the anion ratio should be used. In this case, the average concentration from between the 7 and 10 m depths could be used as input for Cl_{sw} in equation (1). An estimated recharge rate of 5.8 x 10^{-3} cm/yr and a seepage velocity of 5.8 x 10^{-2} cm/yr (assuming a 10% volumetric moisture content) is thus obtained for this borehole. This is consistent with recharge estimates obtained at other locations across the SNL/KAFB area (see Section B.3.3).

One further conclusion that can be drawn from these results is that care should be exercised when applying the chloride mass balance approach for recharge estimation. To permit recognition and correction for the potential effects of reverse osmosis, depth profiles always should be collected for more than one anion (e.g., bromide). This advice was followed in the spatial variability recharge study described in Section B.3.4; though the bromide data were not presented above, the anionic ratios over the entire depths sampled remained constant (and equal to background precipitation at roughly 70:1), and therefore the anion exclusion/reverse osmosis process was not evident and no corrections were required.

B.3.6 Summary of Recharge Estimation Using Environmental Tracers

The results presented above regarding recharge quantification using the chloride mass balance environmental tracer approach indicate quite small recharge rates. The estimate across the SNL/KAFB region ranges between 0.2 to 2.6 mm/yr. This is well below the 1 cm/yr threshold rate identified in the risk-based transport analysis in the 1993 SWHC Project annual report (SNL/NM 1994a); locations with recharge rates above that threshold are likely spots for relatively deep invasion of potential contaminants. From the seven locations where ambient recharge has been quantified using environmental tracers, the estimates are all far below the threshold of concern. This would suggest that for sites where natural recharge is the primary mode of aqueous phase transport, solutes leached from potential contaminants would still be very shallow in the soil profile. Thus if such sites require remediation, it is highly likely that removal by excavation of the shallow soils would be the most expedient remediation technology.

This summary and conclusion should be tempered by the following caveats. These results are not applicable for sites in which the primary aqueous phase transport mode is enhanced fluxes (e.g., spills, leaks, and intentional discharges such as septic tank leachfields). Even some sites that experience only natural water fluxes are expected to have recharge rates much higher than those reported here. The higher recharge rates would most probably correspond to relatively low topographic locations where surface and subsurface water flow paths will converge (see SNL/NM 1994a, Section 5.9; McCord et al. 1991); the end member of this range of locations would be arroyos (recall that several ER sites are located along Tijeras Arroyo).

B.4 REFERENCES

Allison, G. B., G. W. Gee, and S. W. Tyler, 1994. Vadose-Zone Techniques for Estimating Groundwater Recharge in Arid and Semiarid Regions, Soil Science Society of America Journal, Vol. 58, pp. 6-14.

Allison, G. B., 1988. A Review of Some of the Physical, Chemical, and Isotopic Techniques Available for Estimating Groundwater Recharge, in I. Simmers (ed.) Estimation of Natural Groundwater Recharge. D. Reidel Publishers, pp. 49-72.

Ankeny, M., J. Forbes, J. McCord, and J. Leenhoutz, 1996. Liberal Behavior of Conservative Tracers: Effects on Recharge Estimates Using the Chloride Mass Balance Method, submitted to Water Resources Research.

Bowman, Dr. Rob, 1995. Personal communication regarding data collection for chloride and bromide concentrations in precipitation in Socorro, NM.

Brunauer, S., P. H. Emmett, and E. Teller, 1938. Adsorption of Gases in Multimolecular Layers. J. Am. Chem. Sci., Vol. 60, pp. 309-319.

Gee, G. W. and D. Hillel, 1988. Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods. Hydrological Processes, Vol. 2, pp. 255-266.

Karathanasis, A. D. and B. F. Hajek, 1982. Quantitative Evaluation of Water Adsorption on Soil Clays. Soil Science Society of America Journal, Vol. 46, pp. 1321-1325.

McCord, J. T., D. B. Stephens, and J. L. Wilson, 1991. The Importance of Hysteresis and State-Dependent Anisotropy in Modeling Variably Saturated Flows. Water Resour. Res., Vol. 27.

McCord, J. T., C. A. Gotway, and S. H. Conrad, 1996. Impact of Geologic Heterogeneity on Recharge Estimation Using Environmental Tracers. Water Resour. Res., accepted for publication.

Orchiston, H. D., 1954. Adsorption of Water Vapor: II. Clays at 25°C, Soil Science, Vol. 78, pp. 463-479.

Parsons, A. M., J. T. McCord, R. P. Thomas, and M. Furaus, 1994. Using a Geographic Information System to Select Vadose Zone Hydrogeologic Settings for Guiding Site Characterization Activities (SAND93-1843), in press, Sandia National Laboratories, Albuquerque, NM.

Phillips, F. M., 1994. Environmental Tracers for Water Movement in Desert Soils of the American Southwest. Soil Science Society of America Journal, Vol. 58, pp. 15-24.

SNL/NM, 1994a. Sandia National Laboratories/New Mexico. Site-Wide Hydrogeologic Characterization Project: Calendar Year 1993 Annual Report. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

SNL/NM, 1994b. Sandia National Laboratories/New Mexico. SNL/NM Field Operating Procedure 94-62, Bulk Density, Porosity, and Moisture Content of Soils. Environmental Restoration Project, Sandia National Laboratories/New Mexico, Albuquerque, NM.

Stone, W. J., 1984. Recharge in the Salt Lake Coal Field Based on Chloride in the Unsaturated Zone. New Mexico Bureau of Mines and Mineral Resources, Open-File Report 214, 64 pp.

APPENDIX C
1995 SITE-WIDE DRILLING PROJECT

Point of Contact: Walt Foutz (Lamb Associates, Inc.)

CONTENTS

CONTENTS (Concluded)

TABLES

C.1 INTRODUCTION

This appendix summarizes field operations and hydrogeologic data obtained during installation of 12 monitoring/test wells installed at seven locations on Kirtland Air Force Base (KAFB). These wells were installed in 1995 as part of the Site-Wide Hydrogeologic Characterization (SWHC) Project saturated zone investigation. The SWHC Project is part of the Sandia National Laboratories, New Mexico (SNL/NM), Environmental Restoration (ER) Project. More detailed information about each well and drilling location, including geologic setting, well logs, and field notes, is available in contractor reports from the SNL/NM ER Project.

C.2 DRILLING LOCATION SELECTION

SWHC Project drilling locations were selected based on the need for subsurface data in geologically complex areas with uncertain or incomplete information concerning uncertain bedrock geology, geologic structure, and groundwater depth, flow direction, and rate of flow. In addition, several SWHC Project wells were strategically positioned adjacent to ER sites with known groundwater contamination in order to provide hydrogeologic data on a broader lateral and vertical scale than is possible within the confines of a relatively small ER site. These criteria were considered in the prioritization of each site. Five permitted wells were not drilled in 1995 due to budget constraints. The non-drilled locations are discussed in more detail in Section C.5. Locations of all 1995 SWHC Project drilling locations are shown in Figure C-1.

C.3 DRILLING METHODS

Drilling operations at all sites were conducted by U.S. Geological Survey (USGS) personnel and supervised by SNL/NM personnel in accordance with the SWHC Project Field Investigation Plan. Drilling methods included air and mud rotary, and mud rotary, coring performed with a Gardner-Denver 1700 drilling rig. All drilling, well completion, and well development operations were performed by USGS personnel and equipment. Typically, drilling operations were conducted in 10-day-on, 4-day-off work cycles.

Drilling fluid was containerized at the surface in steel mud tanks with attached mud cleaning equipment that included a shale shaker and a centrifugal desander/desilter. Drill cuttings, surplus drilling fluid, and well development water were contained in plastic-lined, 20-yd^3 rolloff dumpsters. At the completion of drilling operations, the rolloffs were emptied on site and the contents were mixed with native soil and restored to natural grade.

Cuttings were logged at the drill site by the SNL/NM Field Operations Supervisor. Drill cuttings samples were taken at 10-ft intervals at the well head by straining drilling fluid returns through a kitchen strainer. Samples were collected continuously and logged at 10-ft intervals. Typical drilling fluid had an estimated viscosity of about 50 sec/qt and a weight of about 9.5 lb/gal., which is heavy enough to suspend coarse sand and gravel. Cuttings samples were lightly rinsed with clean water in standard No. 4 and No. 200 brass sieves to separate grain sizes. The No. 4 sieve collects fine gravel (0.19-in. diameter); the No. 200 sieve retains very fine sand (0.003-in. diameter). Silt and clay is suspended and washes through both sleeves, although light rinsing was used to minimize the loss of fines. These techniques are used to reduce the subjectivity of descriptions of relative grain sizes. Cuttings samples were saved in cloth bags and chip boxes. Cuttings samples were archived in the ER Core Storage transportainer adjacent to Building 6540 in Technical Area III (TA-III).

All wells were constructed in accordance with SNL/NM operating procedures governing the installation of monitoring wells. All wellbores are sealed from the surface by a cement seal extending at least 10 ft below ground surface (bgs). The surface completion is a steel protective casing with a locked lid, surrounded by an approximately 4 ft by 4 ft square concrete apron and four removable steel stanchions.

C.4 SUMMARY OF 1995 DRILLING OPERATIONS

The following subsections are summaries of drilling, well completion, well development, and hydrogeology at each of the seven drilling locations in 1995. Total drilling footage in 1995 was 3150 ft. Twelve new wells were drilled at the seven locations, including three new wells installed in 1994 boreholes. Table C-1 is a summary of important data from all SWHC Project wells drilled in 1995.

C.4.1 Area V North - Wells AVN-1 and AVN-2

Two wells were drilled and completed at the Area V North (AVN) location, AVN-1 and AVN-2 (see Figure C-1). ER sites near the AVN wells include the Liquid Waste Disposal Site (LWDS), Technical Area V (TA-V) Seepage Pits (ER Site 225), and the High Energy Radiation Megavolt Source (HERMES). Known groundwater contamination in this area consists of chlorinated solvents, acetone, and toluene. Toluene has been found in both AVN wells at levels of <1 to 5 μg/l.

The objectives of the AVN wells were to characterize the subsurface geology and complete monitoring/test wells to be used for characterizing groundwater quality and movement in the vicinity of TA-V. An additional objective was to obtain deeper geologic and hydrologic data than was previously available in this area, in an attempt to correlate the stratigraphy and hydrogeology at the Chemical Waste Landfill (CWL) with TA-V.

The AVN drill site was thought to be upgradient or crossgradient from the TA-V contamination plume, based on the existing potentiometric surface map. Two monitoring/test wells were installed to provide qualitative and quantitative hydrogeologic data to compare to existing subsurface data from TA-V.

C.4.1.1 Drilling operations

Drilling operations began at the AVN location on May 9, 1995 and were completed on June 7, 1995. AVN-1 is a 10-in.-diameter borehole that was drilled to a total depth of 650 ft. AVN-1, the pilot hole at this drill site, was drilled to evaluate the stratigraphic section from ground surface to 650 ft. In addition to the lithologic cuttings samples, eight 10-ft cores were taken at 60-ft intervals, beginning at 60 ft below ground surface. These cores were sampled for volatile organic compounds (VOCs) to provide analytical data to support or refute the presence of solvent contamination in the vadose zone. None of the samples taken from unsaturated core had any VOC hits.

AVN-2 was drilled with a 7 7/8-in. bit to a total depth of 630 ft. Three 10-ft core runs were made from just above the water table (490 ft) to 520 ft. Core was taken to characterize lithology at the water table and the screened interval. Cuttings samples were collected at 10-ft intervals, lightly rinsed, and saved in chip boxes.

Table C-1. Summary of 1995 Site-Wide Hydrogeologic Characterization Project Drilling and Well Data

Well	Start Drilling	End Completion	Total Depth (ft)	Casing Total Depth (ft)	Formation	1st Depth to Water (ft)[a]	1st Water Level Elevation (ft)[b]	Top of Casing Elevation (ft)[b]
AVN-1	May 9	May 23	650	600	Santa Fe	508.6	4931.95	5440.55
AVN-2	May 31	June 5	530	520	Santa Fe	507.5	4932.43	5439.93
STW-1	June 13	June 18	180	179.8	Conglomerate	155.8	5377.06	5532.86
TRE-1	July 13	July 31	600	305	Santa Fe	176.5	5318.08	5494.58
TRE-2	July 13	July 31	600	180	Santa Fe	166.7	5327.83	5494.53
LMF-1	Aug 2	Aug 11	410	360	Abo/Madera	345.2	5278.22	5625.42
TRS-2[c]	Sept 6, 94	Sept 9, 95	520	210	Madera	123.6	5654.57	5778.17
TRS-1S[c]	Aug 29, 94	Sept 6, 95	500	215	Madera	123.0	5654.51	5777.51
TRS-1D[c]	Aug 29, 94	Sept 5, 95	500	316	Madera	118.76	5658.48	5777.24
WYO-1	Aug 15	Aug 25	650	570	Santa Fe	515	4876.41	5389.83
WYO-2	Aug 15	Aug 25	650	295	Santa Fe	272.9	5116.76	5389.66
PGS-2	Sept 9	Sept 22	660	655	Santa Fe	546	4859.32	5405.62

[a] Feet below top of casing.
[b] Feet above mean sea level.
[c] Boreholes drilled in 1994. Monitoring wells installed in 1995.

C.4.1.2 Well completion and development

AVN-1 is a 5-in.-diameter Schedule 10 stainless steel pumping/monitoring well completed more than 80 ft below the water table. The borehole was drilled to 650 ft and plugged back to 600 ft with raw bentonite chips. Total casing depth is 595 ft. The completion interval consists of 20 ft of 0.020-in. continuous wire-wound stainless steel screen from 570 to 590 ft with a 5-ft stainless steel sump below the well screen. Because this well would be vigorously pumped during aquifer testing, extra effort was made to ensure that a strong, tight seal separates the grout column from the sand pack. The total seal interval is 488 to 550 ft. Bentonite grout (Volclay) was pumped from 488 ft to ground surface.

AVN-2 is a 4 1/2-in.-diameter Schedule 80 polyvinyl chloride (PVC) monitoring/observation well that is screened across the water table. A 0.020-in. PVC screen was placed from 495 to 515 ft with a sand pack up to 478 ft. The annulus above the bentonite seal was grouted to the surface with Volclay grout. Well completion details are shown in Figure C-2.

Well development was performed on each well after the grout was allowed to set for a minimum of 24 hr. AVN-1 developed quickly due to a relatively high production rate of 10 to 15 gal. per minute (gpm), approximately 80 ft of head at the well screen, and a relatively high permeability in the completion zone. The static water level is 508.60 ft below top of casing. Final water quality parameters are summarized in Table C-2.

Table C-2. Well Development and Water Quality Parameters in the Area V North Wells

Well	Volume Purged (gal.)	Temperature (°C)	Conductivity (mmho)	pH	Turbidity (NTU)	Flow (gpm)
AVN-1	9400	19.9	460	7.4	0.36	15
AVN-2	466	21.6	486	7.3	3.69	0.38

AVN-2 was developed initially using a 5-gal. PVC bailer. This well produces less than 1 gpm, which makes adequate well development difficult. When the development water appeared to be muddy but relatively free of drilling mud, a VOC sample was collected from the bailer. Analytical results obtained the following day showed low levels of acetone, toluene, and chlorinated solvents. Development of AVN-2 was immediately suspended to evaluate the contamination and related waste management issues. Development resumed five weeks later using a Bennett pump. The only solvent that consistently appears in sample data is <5 parts per billion (ppb) toluene. The other solvents appear sporadically and are common laboratory contaminants. Results of final well development water quality monitoring are summarized below.

C.4.1.3 Borehole hydrogeology

The geologic objectives of the AVN wells were to characterize lithology and to determine whether the stratigraphy of the upper Santa Fe Group north of TA-V is correlative with the subsurface at the CWL, at the south end of TA-III.

Cuttings samples were collected and saved at 10-ft intervals from both AVN wells. Approximately 70 ft of core from AVN-1 and 30 ft of core from AVN-2 were also saved in core boxes. The vadose zone core from AVN-1 was used primarily for VOC sample analysis. Core from AVN-2 was used for lithologic description to determine the best screen interval across the water table.

The top of the saturated zone occurs in a massive silty sand at 470 to 540 ft. This unit is predominantly very-fine-grained sand in a silty to clayey matrix, very similar to sediments at about 500 ft depth at the CWL. The fine grain size and low permeability results in the low water production rates observed in AVN-2, which was completed at the water table. Higher permeability is present in the interval 550 to 600 ft bgs. This zone is mostly poorly sorted (well-graded) sand, fine to very coarse grained, with <20% silt and minor gravel. This sequence is also similar to stratigraphy at the CWL. AVN-1 is completed in a coarse- to very-coarse-grained sand with about 20% silt.

AVN-1 is a 5-in.-diameter stainless steel well and is a good candidate for aquifer testing due to relatively high estimated yield, large head, and casing that will accept a high-capacity pump. Waste management problems arising from apparently contaminated groundwater will have to be addressed before large volumes of water can be pumped. The discovery of contaminants in groundwater was unexpected and all data collected will be contributed to the TA-V Seepage Pits, HERMES, and LWDS site characterization efforts.

AVN-2 is a low-yield well that will serve as an observation well. Observations made in AVN-2 while pumping AVN-1 will provide data concerning the hydraulic communication between the water table and the high-permeability sediment below 550 ft. Important depths and elevations are summarized in Table C-1.

C.4.1.4 Borehole geophysics

The open borehole at AVN-1 was logged on May 20, 1995 with USGS equipment and personnel. The log suite included long-short normal resistivity, dual density, natural gamma, neutron, and caliper logs. The top of saturation was indeterminate from the neutron and resistivity logs, probably due to high clay content. The logs were evaluated and well completion options were discussed in a meeting at the well site on May 21, 1995. Based on the geophysical and lithologic logs, it was decided to complete AVN-1 in the high-permeability sand zone at 570 to 590 ft, then drill another borehole to complete AVN-2 at the water table to assist in the TA-V groundwater characterization. Core was taken from 490 to 520 ft to determine the best interval for screen placement in AVN-2. AVN-2 was not logged with geophysical tools.

C.4.1.5 Summary

The wells at the AVN location are positioned to provide a site-wide perspective on groundwater contamination problems at the nearby ER sites: the TA-V Seepage Pits, the HERMES, and the LWDS. Geologic data consist of a detailed lithologic log, approximately 110 cuttings samples representing 10-ft intervals from the surface to 650 ft from two boreholes, nearly 100 ft of core, and a geophysical log suite. The lithologic and geophysical logs indicate that the top of the saturated zone occurs in a massive silty sand with a significant amount of clay that overlies a well-graded permeable sand. This is very similar to the subsurface scenario at the CWL.

Core samples from the vadose zone were analyzed for VOCs. All samples were non-detects. AVN-1 is a 5-in.-diameter stainless steel well completed in a well-graded sand approximately 80 ft below the water table. AVN-2 is a 4 1/2-in.-diameter PVC well completed at the water table. During development, very low levels of solvents were detected in groundwater. This contamination was confirmed by a later episode of well development and sampling. The only solvent that consistently appears in sample data is <5 ppb toluene. Other solvents that appear sporadically are common laboratory contaminants.

The AVN wells provide a location for potential aquifer testing in 1996. Aquifer test data would yield information on anisotropy and vertical and lateral hydraulic conductivities in two distinct zones that may be valuable to nearby ER sites with known groundwater contamination.

C.4.2 Solar Tower West - Well STW-1 and Borehole STW-2

The Solar Tower West (STW) location is near the southern edge of KAFB, east of Thunder Range, and west of the Solar Tower, at the intersection of Magazine and Isleta Roads. STW-1 and STW-2 are paired boreholes drilled at STW (see Figure C-1).

The objectives of drilling at STW were to determine the vertical and lateral extent and characteristics of the conglomerate that forms the Travertine Hills and to provide groundwater elevation and flow direction information. STW is located within a fault complex consisting of the Tijeras, Sandia, and Hubbell Springs faults. This is a hydrologic transition zone with water levels decreasing from east to west across the fault complex. Water levels in the South Fence Road (SFR) wells that are completed in the Santa Fe Group vary from about 90 ft or 5306 feet above mean sea level (famsl) at SFR-1 to about 162 ft (5332 famsl) at SFR-3. West of the fault zone at CWL-MW6U, the depth to water is 481 ft (4936 famsl). STW is in the fault complex and the depth to water was anticipated to be 90 to 162 ft.

C.4.2.1 Drilling operations

Drilling at STW-1 began on June 13, 1995 and was completed on June 18. The hole was drilled with mud rotary methods and a 7 7/8-in. bit to 157 ft. Core runs were made in three 10-ft intervals with total recovery of 27 ft. Drilling fluid circulation was abruptly lost at 157 ft and never regained, although drilling continued to 180 ft. A temporary casing was installed at 166 ft to evaluate the water level and lost circulation zone, which resulted in a water level of 150.5 ft after well development.

STW-2 was drilled after completing STW-1. The hole was drilled to a total depth of 521 ft with a total of four core runs and 34.8 ft of recovery. Circulation was lost at 314 ft, at which point the decision was made to attempt to regain circulation using lost circulation material (LCM). A 600-gal. mixture of natural gel, Volclay, and Magmafiber (an LCM product) was injected and lost while drilling from 314 to 318 ft. The next day, 750 gal. of drilling fluid were added and lost. Subsequently, 300 gal. of neat cement and 500 lb of bentonite chips were added, bringing the material level to 276 ft. The following morning the chips were at 255 ft. Drilling resumed and circulation was regained immediately. Drilling continued to the total depth of 521 ft without further lost circulation. STW-2 was plugged with bentonite chips and a cement plug at the surface and abandoned.

C.4.2.2 Well completion and development

Based on the water level in the temporary completion in STW-1, the decision was made to construct a permanent monitor well screened across the lost circulation zone. STW-1 is a 4 1/2-in.-diameter Schedule 80 PVC well with a total depth of 179.8 ft. A 0.020-in. slotted PVC screen was placed at 149.8 to 169.8 ft with a 10-ft sump below the screen. A 10/20 silica sand pack was placed from 119 to 180 ft. Above the sand pack from 100.5 to 119 ft is a bentonite seal followed by a 1-ft layer of 10/20 sand. Above this, the annulus was filled with a Volclay bentonite slurry from 99.5 ft to the surface. Well completion details are shown in Figure C-3.

STW-1 was bailed dry nine times between June 19 and June 27. Water was added and the well was surged twice. Each successive bailing resulted in a larger amount of water being removed prior to the well going dry. Approximately 150 gal. of groundwater (not including the added water) were removed during development. Groundwater quality parameters at the conclusion of well development were as follows: pH of 7.63, electrical conductivity of 550 millimhos (mmhos), temperature of 23.7°C, and turbidity < 1000 nephelometric turbidity units (NTU). The static water level was 153.9 ft on June 27, 154.0 ft on July 17, and 155.8 ft on August 3.

C.4.2.3 Borehole hydrogeology

Lithology at the STW location is a coarsening downward sequence of sandy silt, gravelly sand, and cobbly gravel from 22 to 64 ft. Conglomerate is the dominant lithology from 64 ft to total depth. The conglomerate is generally poorly to moderately cemented with calcium carbonate. The composition is approximately 60% limestone clasts, 10 to 15% quartzite clasts, 10% siltstone (Abo Formation), and 15 to 20% fine-grained matrix. The clasts are subangular with grain sizes ranging from fine sand to coarse gravel. Bedding planes are visible in the borehole video and core and average about 30 to 35 degrees from horizontal.

The hydrologic objective of the STW location was to determine the depth to water. After development, the groundwater level was 155.8 ft below top of casing.

C.4.3 Thunder Range East - Wells TRE-1 and TRE-2

The Thunder Range East (TRE) location is near the southern boundary of KAFB, east of Thunder Range, and southwest of the Solar Tower. TRE-1 and TRE-2 are nested wells located approximately 0.75 mi north of the southern edge of KAFB, east of Thunder Range, and southwest of the Solar Tower (see Figure C-1). The location is approximately 0.6 mi southwest of the intersection of Magazine and Isleta Roads.

TRE is located within a fault complex consisting of the Tijeras, Sandia, and Hubbell Springs faults. This is a hydrologic transition zone with water level elevations decreasing from east to west across the fault complex. Water levels in the SFR wells (see Figure C-1), which are completed in the Santa Fe Group, vary from approximately 90 ft (5306 famsl) at SFR-1S to approximately 162 ft (5333 famsl) at SFR-3S. Table C-3 lists completion information for these and other wells in the vicinity of TRE. The recently completed well STW-1, located approximately 0.6 mi northeast of TRE, has a depth to water of about 155 ft (5378 famsl). West of the fault zone at the CWL, the depth to water is

Table C-3. Completion Information for Wells in the Vicinity of Thunder Range East

Location	Top of Casing Elevation (ft)[a]	Screen Interval (ft)[b]	Total Depth (ft)[b]	Depth to Water in 1995 (ft)[c]	Water Level Elevation (ft)[a]
SFR-1S	5396.49	152-172	182	90.54	5305.95
SFR-2S	5430.10	97-117	122	101.74	5328.36
SFR-3S	5495.57	182-212	222	162.14	5333.43
SFR-4P	5570.66	344-354	364	175.41	5395.25
SFR-4T	5571.28	340-360	380	165.65	5405.63
STW-1	5532.86	149.8-169.8	179.8	154.66	5378.20
CWL-MW6U	5416.78	480-500	502	481.34	4935.44

[a] Feet above mean sea level.
[b] Feet below ground surface.
[c] Feet below top of casing.

481 ft (4936 famsl), which is representative of regional water levels. TRE is in the fault complex and therefore it was anticipated that the depth to water would fall between 5306 and 5405 famsl (between approximately 90 and 189 ft bgs).

C.4.3.1 Objective

The TRE drill site was selected to provide geologic and hydrologic data in the southern region of KAFB. This area of KAFB is characterized by varying depths to water and complicated geologic sequences as a result of the presence of the Sandia, Tijeras, and Hubbell Springs faults.

The faults result in the need for drilling information to determine the subsurface stratigraphy in the area of TRE. Before drilling, possibilities included clastic sequences such as the Travertine Hills conglomerate or the Upper Santa Fe Unit. The possibility also exists that a bedrock unit such as the Permian Abo Formation or the Pennsylvanian Madera Formation could be encountered at depth.

Hydrologic data in this area were needed to help reduce uncertainty about groundwater elevation and flow direction. Additionally, the TRE site is located east of Thunder Range which contains numerous ER sites, and hydrologic information such as flow direction and aquifer characteristics aids in characterizing these ER sites.

C.4.3.2 Drilling operations

Rotary drilling at TRE began on July 13 and was completed on July 17, 1995. The hole was drilled using rotary mud with a 7 7/8-in. tricone bit to 5 ft and an 8-in.-diameter surface casing was set to 4 ft. The hole was then drilled to a total depth of 600 ft using mud rotary and a 6 1/4-in. tricone bit. No coring was performed at TRE. The hole was backfilled with bentonite chips to 266 ft and reamed from surface to 309 ft using mud rotary and a 9 7/8-in. tricone bit prior to installation of the well.

C.4.3.3 Well completion and development

The borehole was logged following drilling to total depth. Review of the logs indicated that saturation was at approximately 151 ft in a fine-grained material. The logs also revealed that the first permeable interval was approximately 255 to 295 ft. Based on this interpretation, it was determined that a deep "pumping" well would be completed to approximately 300 ft and a shallow "observation" well would be completed to approximately 180 ft. Well completion relationships are shown in Figure C-4.

TRE-1 was installed to a total depth of 305 ft using 4 1/2-in.-diameter Schedule 80 PVC casing and well screen. The 0.020-in. slotted PVC screen was placed from 255 to 295 ft with a 10-ft sump from 295 to 305 ft. A 10/20 silica sand pack was placed from 240 to 309 ft. Above the sand pack from 220 to 240 ft is a bentonite pellet seal followed by bentonite chips from 180 to 220 ft.

TRE-2 was installed to a total depth of 180 ft, placed on top of the bentonite chips, using 2-in.-diameter Schedule 80 PVC casing and well screen. The 0.020-in. slotted PVC screen was placed from 150 to 170 ft with a 10-ft sump from 170 to 180 ft. A 10/20 silica sand pack was placed from 133 to 180 ft. Above the sand pack from 111 to 133 ft is a bentonite pellet seal followed by a Volclay slurry from the surface to 111 ft.

Development of TRE-1 was performed with air on July 29 and 30, 1995. Approximately 14,135 gal. of water were removed during well development. Discharge rates varied from 1 to 32 gpm. The parameters had ending values: pH of 7.49, electrical conductivity of 1436 mmhos, temperature of 18.8°C, and turbidity of 16.7 NTU. The depth to water was 173.7 ft on July 31, and 173.2 ft on August 2, 1995.

TRE-2 was developed with air on July 30 and 31, 1995. The depth to water prior to development was approximately 175 ft. A process of blowing the well dry, adding approximately 10 gal. of water, and blowing the well dry again was repeated approximately 10 times. Approximately 100 gal. of water were added and a total of approximately 115 gal. were removed. The well was developed with a bailer on August 2, 1995 when approximately 4.3 gal. were removed. The parameters had ending values of: pH of 6.77, electrical conductivity of 676 microsiemens, temperature of 24.2°C, and turbidity of >1000 NTU. TRE-2 had a depth to water of 163.20 ft prior to bailing and a depth to water of 164.17 ft on August 3.

C.4.3.4 Borehole hydrogeology

The lithology of TRE is summarized in Table C-4.

The stratigraphy consists of interbedded silt, sand, and gravel of the Upper Santa Fe unit. Characteristic of alluvial fan lithofacies, the sand is generally poorly sorted, subrounded to subangular. The gravel is generally fine, also subrounded to subangular. The unit is poorly cemented with none to little cementation visible on the grains.

Hydrologically, the purpose of TRE-1 was to investigate the depth to groundwater beneath this area of KAFB. The first water encountered was picked from the geophysical logs at 151 ft. Due to the abundance of fine-grained material (silt) and the resulting low permeabilities from 150 to 170 ft, it was decided to place a deep well in a more permeable zone and to place an observation well at the top of the water table.

Table C-4. Summary of Dominant Lithologies in the Thunder Range East Boreholes

Depth Interval (ft)[a]	Dominant Lithology
0-150	Gravelly sand/sandy gravel, minor silt
150-250	Silty sand/gravelly sand
250-340	Sand/gravelly sand
340-480	Silty sand/sand, minor gravel
480-600	Silty sand/sand
[a]Feet below ground surface.	

TRE-1 was placed with a screen from 255 to 295 ft and TRE-2 was placed with a screen from 150 to 170 ft. The deep completion (TRE-1) produced up to 32 gpm during development and had a depth to water of 173.20 ft on August 2, 1995. TRE-2 produced very little water and had a depth to water of 164.17 on August 3, 1995. Using the center of the interval from the top of the sand pack to the bottom of the screen at each well and the given water levels, a downward vertical gradient of 0.0778 is calculated at TRE.

C.4.3.5 Summary

The TRE drill site was selected to provide geologic and hydrologic data in the southern region of KAFB. The objectives included determining the bedrock geology and the depth to water. This area of KAFB is characterized by varying depths to water and complicated geologic structure as a result of the presence of the Sandia, Tijeras, and Hubbell Springs faults.

The stratigraphy consists of generally poorly cemented, interbedded silt, sand, and gravel of the Upper Santa Fe unit. TRE-1 was completed to 305 ft with a screen from 255 to 295 ft. The depth to water following development was 173.20 ft. TRE-2 was completed to 180 ft with a screen from 150 to 170 ft. The depth to water following development was 164.17 ft.

C.4.4 Large Melt Facility - Well LMF-1

One well was drilled and completed at the Large Melt Facility (LMF), located approximately 200 yd north of the Large Melt Facility and 1/2 mi south of the junction of Lovelace Road and Coyote Springs Road (see Figure C-1). ER sites near the LMF-1 well include Sites 154, 103, 117, and 150. This is an area for which very little subsurface data are available. It is geologically complex, situated between the Tijeras and Sandia fault zones, with nearby Madera outcrops to the east and the Travertine Hills to the west.

The primary objective of the LMF-1 well was to characterize subsurface geology in the area between Manzano Base and the Travertine Hills. A secondary objective was to install a monitoring/test well to be used for characterizing groundwater quality and movement in this area. The well will provide water level and water quality information.

C.4.4.1 Drilling operations

Drilling operations began at the LMF location on August 2 and were completed on August 14, 1995. LMF-1 is an 8-in.-diameter borehole that was drilled to a total depth of 410 ft. Lithologic cuttings samples were collected at 10-ft intervals, lightly rinsed to remove drilling mud, logged, and saved in chip boxes.

In addition to lithologic samples, three 10-ft cores were taken from the intervals 8 to 18 ft, 120 to 130 ft, and 400 to 410 ft. These rock cores were used for lithologic determination of hard-cemented alluvial material, bedding plane measurement of the dip of the Abo Formation, and lithologic description of the Madera Formation, respectively. Total core recovery was 26 ft, which was described, boxed, labeled, and archived in the ER Field Office Core Transportainer.

C.4.4.2 Well completion and development

LMF-1 is a 4 1/2-in.-diameter Schedule 80 PVC monitoring well completed at the bottom of the Abo Formation. The borehole was drilled to 410 ft and plugged back to 370 ft with medium raw bentonite chips. The completion interval consists of 40 ft of 0.020-in. slotted PVC screen from 310 to 350 ft. A 10-ft Schedule 80 PVC sump extends below the screen to the total casing depth of 360 ft. A bentonite seal from 260 to 293 ft separates the grout column from the sand pack. Bentonite grout (Volclay) was pumped from 260 ft to ground surface.

Initial well development was conducted using the air-lift method. The well was jetted and allowed to recover about 45 min to 1 hr before jetting again. This cycle was repeated for the entire first day. Recovery was very slow, averaging about 1 ft per hr. The second day, water was repeatedly added to the casing and air-lifted out to attempt to remove drilling mud or silt that was possibly blocking the screen. This continued for a half day, when the decision was made to discontinue using the rig because of the very low production rate. Well development resumed later using water injection and removal by a Bennett pump. This method was used for three days, resulting in the completion of well development.

C.4.4.3 Borehole hydrogeology

The alluvial material at this location is only 15 ft thick and consists of poorly sorted sandy gravel, sandstone, and well-cemented conglomerate. The conglomerate is quite hard and similar in appearance to the conglomerate exposed nearby in the active channel of Arroyo del Coyote. The top of the Permian Abo Formation was encountered at 15 ft and verified by coring after the well was completed and developed. The Abo Formation consists of homogeneous brick-red claystone in the interval 15 to 320 ft. The lower 30 ft consists of siltstone, sandstone, and sandy shale. The lithologic and geophysical logs are presented in Figure C-5.

The top of the Pennsylvanian Madera Formation was encountered at 352 ft. The formation top was distinguished by a cuttings sample color change from red to dark gray in the 350 to 360 ft sample and was picked from geophysical logs. The Madera Formation is extremely weathered at this location and consists of sandy and silty dark gray clay, siltstone, and shale with calcareous fracture fillings and bedding planes, observed in core samples, ranging from 25 to 40 degrees from horizontal.

The final water level is approximately 345 ft bgs, which is in the Abo Formation, about 7 ft above the weathered top of the Madera Formation. This well is a very slow water producer, < 1/2 gpm, which is not surprising considering the clayey lithology. The objectives of determining bedrock geology and the depth to water were achieved.

C.4.5 Wyoming and Ordnance Road - Wells WYO-1 and WYO-2

The Wyoming and Ordnance Road (WYO) location is west of Technical Area II (TA-II), north of the intersection of Wyoming and Pennsylvania Boulevards, and south of the intersection of Wyoming Boulevard and Ordnance Road (see Figure C-1). The WYO location was selected to provide geologic and hydrologic data in the northern part of KAFB. The objective was to determine a regional water level and to further define the presence or absence of the perched aquifer system found in TA-II (TA2-NW1-325), as well as in Tijeras Arroyo (TJA-2). It was determined in 1994, with the installation of the PGS-1 well, that the perched system did not extend to the PGS-1 location (see Figure C-1). In addition, the WYO well location was chosen to serve as a monitor well for the nearby TA-II ER sites.

An evaluation of monitor wells in the area of WYO was made prior to drilling. The WYO location is approximately 0.7 mi northeast of a cluster of four KAFB monitor wells and approximately 0.6 mi west of TA-II monitor wells TA2-NW1-595 and TA2-NW1-325 (see Figure C-1). Monitor wells TJA-2 and PGS-1 are located approximately 1.0 mi southeast and 1.1 mi north of the WYO location, respectively. Completion information, including water level elevations in these wells, is included in Table C-5. Note that although the depth to water in PGS-1 has fluctuated above the bottom of the screen (528 ft), the water level has been below the screen since March 1995. Therefore the depth to water is assumed to be deeper than 528 ft. The four KAFB wells and TA2-NW1-595 have water level elevations ranging from approximately 4875 to 4888 famsl. It is believed that these wells reflect the regional water table. The TA2-NW1-325 and TJA-2 wells have water level elevations of approximately 5108 and 5076 ft, respectively. These water level elevations are believed to be associated with a perched aquifer system.

Based on the information above, and an approximate ground surface elevation of 5390 famsl at WYO, regional and perched water level elevations at the location were estimated. If the perched system existed at the WYO location, it could be at approximately 280 ft (5110 famsl) and the regional water level would be at approximately 510 ft (4880 famsl).

C.4.5.1 WYO drilling operations

Drilling at WYO began on August 15 and was completed on August 24, 1995. The hole was drilled with a 12 1/4-in. bit with rotary air to 4 ft and a 12-in. surface casing was set. The hole was then drilled to a total depth of 650 ft using mud rotary and a 9 7/8-in. tricone bit. No coring was performed. The borehole was backfilled with bentonite chips to 572 ft prior to installation of the two wells.

C.4.5.2 WYO-1 and WYO-2 well completion and development

The borehole was logged following drilling to total depth. Review of the logs indicated that initial saturation was at approximately 262 ft and the first permeable interval below saturation was approximately 272 to 280 ft. This was believed to represent the perched system. Saturation and permeability was also picked from 510 to 562 ft, which represents the regional water table. Based on this

Table C-5. Completion Information for Wells in the Vicinity of Wyoming and Ordnance Road

Well Name	Top of Casing Elevation (ft)[a]	Screen Interval (ft)[b]	Total Depth (ft)[b]	Depth to Water in 1995 (ft)[c]	Water Level Elevation (ft)[a]
KAFB-501	5358.04	473-493	503	480	4878.04
KAFB-502	5361.21	476-496	506	486	4875.21
KAFB-503	5357.72	471-491	501	480	4877.72
KAFB-504	5354.22	470-490	500	479	4875.22
TA2-NW1-595	5418.59	585-595	598	530	4888.59
TA2-NW1-325	5419.83	295-325	330.3	309	5110.83
TJA-2	5350.53	275-295	305	273	5077
PGS-1	5404.74	503-513, 518-528	538	>528	>4876.74

[a] Feet above mean sea level.
[b] Feet below ground surface.
[c] Feet below top of casing.

interpretation, it was determined that a deep well would be completed to approximately 570 ft to monitor the regional water level and a shallow well would be completed to approximately 295 ft to monitor the perched system. A completion diagram for the WYO wells is presented in Figure C-6.

WYO-1 was installed to a total depth of 570 ft using 4 1/2-in.-diameter Schedule 80 PVC casing and well screen. The 0.020-in. slotted PVC screen was placed from 510 to 560 ft with a 10-ft sump from 560 to 570 ft. A 10/20 silica sand pack was placed from 476 to 572 ft. Above the sand pack from 299 to 476 ft is a bentonite chip seal installed to isolate WYO-1 from WYO-2.

Development with air was performed on August 27 and 28, 1995. Approximately 1080 gal. of water were removed during well development. Discharge rates varied from 0.5 to 20 gpm with most development occurring in the lower range of from 0.5 to 2.0 gpm. The parameters had the following ending values: pH of 7.66, electrical conductivity of 583 mmhos, temperature of 25.1°C, and turbidity of 98.8 NTU. Several depths to water recorded at WYO-1 and WYO-2 following development are listed in Table C-6.

WYO-2 was installed to a total depth of 295 ft using 2-in.-diameter Schedule 80 PVC casing and well screen. The 0.020-in. slotted PVC screen was placed from 265 to 285 ft with a 10-ft sump from 285 to 295 ft. A 10/20 silica sand pack was placed from 228 to 299 ft. Above the sand pack from 215 to 228 ft is a bentonite pellet seal followed by a Volclay slurry from the surface to 215 ft.

WYO-2 was developed with air on August 28 and 29, and again on September 26, 1995. In August, the air was turned on and off until approximately 20 gal. of water had been removed. In addition, approximately 10 gal. of water were added and removed from the well. The final parameters measured were pH of 7.61, electrical conductivity of 545 mmhos, temperature of 22.4°C, and turbidity of

Table C-6. WYO-1 and WYO-2 Water Levels Following Development

Date (1995)	WYO-1 Top of casing elevation: 5389.83 ft[a]		WYO-2 Top of casing elevation: 5389.66 ft[a]	
	Depth to Water (ft)[b]	Water Level Elevation (ft)[a]	Depth to Water (ft)[b]	Water Level Elevation (ft)[a]
8/30	516.30	4873.53	273.35	5116.31
8/31	513.42	4876.41	271.50	5118.16
9/13	514.89	4874.94	272.98	5116.68
9/26	Not measured	Not measured	272.94	5116.72
10/11	507.80	4882.03	271.68	5117.98
11/3	507.88	4881.95	271.71	5117.95

[a] Feet above mean sea level.
[b] Feet below top of casing.

>1000 NTU. In September, a similar air development method was used to remove approximately 20 gal. of water.

C.4.5.3 Hydrology summary

Hydrologically, the purpose of drilling WYO was to establish a regional water level and, if it were detected, to investigate the possibility of perched or mounded water above the regional water level. The first water was picked from the geophysical logs at approximately 262 ft, with a permeable interval from approximately 272 to 280 ft. The regional water level was picked from the geophysical logs at approximately 505 ft with permeable intervals from 510 to 530 ft and 545 to 562 ft. It was decided to place a deep completion (WYO-1) with a screen from 510 to 560 ft and a shallow completion (WYO-2) with a screen from 265 to 285 ft.

Following development, WYO-1 and WYO-2 had depths to water of 507.88 ft and 271.71 ft, respectively, on November 3, 1995. This indicates that the perched or mounded system beneath TA-II extends west to at least the WYO location.

C.4.6 Parade Ground South - Well PGS-2

The Parade Ground South (PGS) location is near the northwest corner of Technical Area I (TA-I) just south of the KAFB parade ground (see Figure C-1). PGS-2 was drilled approximately 30 ft north of PGS-1, a well installed in August 1994. The drilling and installation of PGS-1 is described in the Summary of Field Operations - Technical Area I, Well PGS-1 (Fritts and McCord 1995).

PGS-1 was completed to a total depth of 538 ft with screen intervals from 503 to 513 ft and 518 to 528 ft. A 5-ft blank separates the two screens to allow for an effective 25-ft screen. The depth to water at PGS-1 fluctuated from 511 ft to below the screen from August 1994 until March 1995. Since March, the depth to water has been 528 ft (the bottom of the screen). It is believed that water levels in the well are fluctuating below the screen as a result of the pumping of production wells located 0.75 mi to 1 mi from PGS-1. It was determined that a deeper well was required at this location to allow for the fluctuations. The fine-grained material present in the screened interval may also be affecting the show of water levels in this well. The PGS-2 well is a replacement for PGS-1.

The geophysical logs for PGS-1, which was drilled and logged to 750 ft, were used to assist in picking a completion interval for PGS-2. The first saturation was picked at approximately 500 ft in the PGS-1 borehole with intervals at 560 to 570 ft, 590 to 600 ft, and 630 to 640 ft exhibiting porosity. Therefore, a total depth of 650 ft was estimated for PGS-2.

C.4.6.1 PGS-2 drilling operations

Drilling at PGS began on September 9 and was completed on September 19, 1995, including a four-day break. The hole was drilled with a 12 1/4-in. bit with rotary air to 4.5 ft and a 12-in.-diameter surface casing was set. The hole was then drilled to a total depth of 660 ft using mud rotary and a 9 5/8-in. tricone bit. No coring was performed.

C.4.6.2 PGS-2 well completion and development

The borehole was logged following drilling to total depth. Review of the logs indicated that first water was at approximately 526 ft. Although the lithology is dominated by fine-grained material from 500 to 650 ft, intervals of sand with some porosity were picked at 540 to 546 ft, 558 to 570 ft, 590 to 605 ft, and 630 to 645 ft, similar to what was seen in PGS-1. It was therefore determined that a well would be installed to 655 ft with three screen intervals.

PGS-2 was installed to a total depth of 655 ft using 5-in.-diameter Schedule 10 stainless steel casing and well screen. The 0.020-in. slotted PVC screen was placed from 535 to 565 ft, 585 to 595 ft, and 625 to 645 ft. The screen intervals were isolated with bentonite chips placed from 567 to 580 ft and 596 to 616 ft. The 10/20 sand packs were placed in the screen intervals and to 485 ft. Above the sand pack, from 480 to 485 ft, is a bentonite pellet seal followed by a Volclay slurry from 480 ft to the surface. Figure C-7 is a well completion schematic for PGS-2.

Development with air was performed on September 23, 24, and 25, 1995. Approximately 11,400 gal. of water were removed during well development. Discharge rates varied from 3 to 6.5 gpm the first day. The second and third days the rate was cycled from 8 to 16 gpm. By the third day, after removing almost 10,000 gal., the turbidity dropped below 1000 NTU. The parameters had the following ending values: pH of 7.89, electrical conductivity of 513 mmhos, temperature of 21.6°C, and turbidity of 56.6 NTU.

C.4.6.3 Hydrology summary

Hydrologically, the purpose of drilling PGS-2 was to determine a regional water level. A previously installed monitor well, PGS-1, provided information that the water level in this area fluctuates as a result of KAFB production wells located within 1 mi of the PGS location.

A well with three screens was installed to 655 ft with a sand pack interval from 485 to 655 ft. The seals between the screens will allow for packers to be installed to monitor or test discrete intervals. The well produced up to 16 gpm during development with final turbidity readings below 100 NTU. The depth to water was 509.60 on November 3 and 532.93 on December 5, 1995. The depth to water is being monitored with a transducer to better quantify the well response to nearby pumping.

C.4.7 Target Road South - Wells TRS-1 and TRS-2

The Target Road South (TRS) drilling location is south of Lake Christian approximately 1/3 mi east of Lovelace Road on the south side of Target Road (also known as Isleta Road) (see Figure C-1). Wells TRS-1 and TRS-2 were drilled at the TRS site in 1994 and left as open holes below surface casing. In 1995, both holes were re-entered and completed with screened well casing. This site was selected to provide bedrock lithology information and a bedrock aquifer test location. Two wells were required to provide a pumping well and an observation well for future hydrologic testing.

C.4.7.1 Drilling operations

Drilling at TRS-1 began on August 29, 1994. The top of the Madera Formation was encountered at 122 ft. Steel casing was set through the alluvial cover and into the bedrock contact. A 6-in.-diameter steel casing with welded joints was set to 134 ft and cemented in place. Drilling resumed using air mist rotary methods and a 6-in. air hammer bit. At 153 ft, the well started producing water at an approximate rate of 25 gpm from fractured limestone. From this depth to 500 ft, water-producing fractures and lost circulation zones were frequently encountered. Total depth of 500 ft was reached on September 4, 1994.

Drilling at TRS-2 began on September 6 and was completed at a total depth of 520 ft on September 19, 1994. The top of the Madera Formation was encountered at approximately 114 ft. A 6-in.-diameter steel casing was set to 117 ft. Similar to TRS-1, circulation was lost several times while drilling the Madera Formation. This was frequently followed by production of large amounts of water.

C.4.7.2 Well completion

TRS-1 and TRS-2 were left as open boreholes until 1995. Both holes were re-entered and completed as shown in the well completion diagram in Figure C-8. Both boreholes were inspected and videotaped with a downhole camera immediately after drilling, and these tapes were used to design the well completions described below.

Steel surface casing in the TRS-1 borehole extends from the surface to 134 ft, effectively sealing the alluvial material from the wellbore. TRS-1 was completed as a dual well with a deep and a shallow screened interval. The 2-in.-diameter PVC wells are named TRS-1D and TRS-1S. The borehole was plugged back from 500 ft to 345 ft with 3/8-in. pea gravel, which was topped with 13 ft of cement and allowed to cure overnight. Well casing consisting of 2-in.-diameter Schedule 80 PVC was run to 316 ft, with a 40-ft screened interval of 266 to 306 ft (0.020-in. slots). The well screen is surrounded by 10/20 silica sand up to 247 ft. A bentonite chip seal separates the upper and lower completions.

TRS-1S is a 2-in.-diameter PVC well with a 0.020-in. slotted PVC screened interval of 165 to 205 ft. The sand pack is 10/20 silica sand extending up to 151 ft. Bentonite chips were used for the seal above the sand pack. The annular space between the PVC casing and steel surface casing is filled with 3/8-in. pea gravel.

Because these wells were drilled with fresh water and air and are all completed in fractured bedrock with very high transmissivities, well development was not necessary.

TRS-2 is a shallow completion in the same interval as TRS-1S and is designed to be a pumping well for aquifer testing in conjunction with TRS-1S. Steel surface casing in TRS-2 extends from ground surface to 117 ft. The borehole was plugged back to 220 ft with pea gravel and an 8-ft-thick cement plug. The well casing is 5-in.-diameter Schedule 10 stainless steel with a 40-ft .020-in. screen matching the interval in TRS-1S. TRS-2 is an open completion void of sand pack or other material in the annular space from 212 to 34 ft. A cement plug was placed from 34 ft to ground surface to seal the top of the hole.

C.4.7.3 Borehole hydrogeology

There was no evidence of water in the alluvial material at the TRS drill site. In TRS-1, the first water-bearing zone was found at 153 ft in fractured limestone and produced an estimated 25 gpm. Circulation was lost from 174 to 182 ft, followed by an increase in water discharge to about 50 gpm. At 195 to 198 ft, circulation stopped again, followed by an increase in formation water production to more than 75 gpm. From 200 to 260 ft, circulation was lost and recovered several times without an increase in water production. This pattern continued to 324 ft, where the well produced approximately 125 to 150 gpm. Lost circulation occurred repeatedly to total depth of 500 ft without an increase in water production rates.

Since completing TRS-1S/1D, the difference between water levels in the upper and lower screens has slowly increased. Water levels measured below top of casing are summarized in Table C-7 below.

Table C-7. Summary of Water Level Measurements in TRS-1 and TRS-2

Date	TRS-1S	TRS-1D	TRS-2
9/9/95	123.00	118.76	123.63
9/13/95	124.88	118.6	125.41
10/11/95	128.49	117.9	129.04
11/3/95	129.39	117.91	129.94

Two aspects of this brief history of water levels are interesting. The deeper well has a significantly higher water level than the two shallow wells, indicating that an upward vertical gradient is present in the bedrock aquifer. While the water levels in the deep well are relatively stable, heads in the shallow wells are steadily declining. This results in a head difference that has increased from about 5 ft initially to about 12 ft at the end of 1995.

The newly recompleted TRS wells provide a good location to conduct aquifer tests to assess hydraulic properties of the Madera Formation and to assess innovative aquifer testing methods. There is a potential for gaining valuable information from this location.

C.5 PERMITTED LOCATIONS NOT DRILLED IN 1995

Five wells that were proposed to the 1995 SWHC Project will not be drilled by the SWHC Project. All the necessary permits have been obtained, including a Categorical Exclusion from the National

Environmental Policy Act (NEPA) and a KAFB Real Estate Permit. Therefore, it would be a simplified process for another interested entity to drill at these locations. These sites are shown in Figure C-1 as proposed wells. The Coyote Arroyo (CYA) drill site is located at Coyote Springs. The Arroyo Confluence South (ACS) drill site is near the south side of the junction of Arroyo del Coyote and Tijeras Arroyo. The Solar Tower South (STS) drill site is directly south of the Solar Tower in a KAFB practice drop zone. Two wells, MBW-1 and MBW-2, were proposed at the Manzano Base West (MBW) drill site, directly west of Manzano Base on the Sandia fault.

C.6 REFERENCES

J. Fritts and J. McCord, 1995. Summary of Field Operations - Technical Area 1, Well PGS-1. SAND94-3123, Sandia National Laboratories/New Mexico, Albuquerque, NM.

APPENDIX D
1995 AQUIFER TESTING PROGRAM

Point of Contact: Erik Storms (INTERA, Inc.)

CONTENTS

TABLES

D.1 INTRODUCTION

As part of the Site Wide-Hydrogeologic Characterization (SWHC) Project, a series of aquifer tests (11 slug tests and 5 pumping tests) were performed between April and September, 1995. The objective of these tests was to develop an understanding of the basic aquifer parameters controlling the flow of water in the aquifer being tested. The results of the aquifer test analysis will be used in regional flow models and to assess possible contaminant transport. This program included tests within different intervals in the Upper Santa Fe Group aquifer (TJA-2, PL-1, and MRN-1 locations) and in the Abo Formation bedrock aquifer (TRN-1 location).

Aquifer well testing provides estimates of hydraulic parameters by measuring the effects of inducing stress in an aquifer around a well. The stress can be induced by withdrawing water from the well or injecting water into the well. A withdrawal or injection made continuously over an extended period of time is referred to as a pumping test. An instantaneous withdrawal or injection of a discrete volume is known as a slug test. Slug tests are faster and easier to perform than pumping tests, but only stress that portion of the aquifer immediately around the borehole of the tested well. Therefore, slug tests are more affected by local heterogeneities and the disturbed area around the well caused by drilling and well installation, than are pumping tests.

The two main parameters identified by aquifer testing are transmissivity and storativity or specific yield. Transmissivity is the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient. Storativity and specific yield are the volume of water an aquifer releases from storage per unit surface area of the aquifer per unit change in head. Storativity refers to water released from elastic storage and specific yield refers to water released due to drainage in an unconfined aquifer. Values for storativity in an unconsolidated porous media range from 0.005 to 0.00005 (Freeze and Cherry 1979). Values for specific yield in unconsolidated porous media range from 0.3 to 0.001 (Freeze and Cherry 1979). Transmissivity and storativity/specific yield depend on the thickness of the aquifer. Hydraulic conductivity is the rate at which water is transmitted through a unit area of aquifer under a unit hydraulic gradient and is equal to the transmissivity divided by the aquifer thickness. Aquifer testing may also provide other information about the formations being tested, such as anisotropy, the presence of boundaries, and the hydraulic connection to other formations.

The parameters obtained from aquifer well tests are essential to the process of modeling the possible transport of contaminants in the groundwater. On a local scale, such as at a Solid Waste Management Unit (SWMU) site, aquifer parameters are needed to assess the possibility of contaminants migrating off the site. On a larger scale, the parameters are needed to predict the possible long-term risk of contaminant movement to water supply wells. Because of small- and large-scale heterogeneities, it is necessary to obtain aquifer parameters at different locations and different depths in order to characterize the overall range of the parameters.

During 1995, aquifer tests were performed at the Chemical Waste Landfill (CWL) SWMU site in Technical Area III (TA-III), the Liquid Waste Disposal System (LWDS) SWMU site in TA-V, and those SWHC Project monitoring wells installed in 1994 (see Plate II). In addition, pressure transducers were installed in monitor wells located in TA-II and were used as observation wells to determine the influence of pumping from Kirtland Air Force Base (KAFB) production wells. The testing performed at the CWL, LWDS, and TA-II sites was in support of the Environmental Restoration (ER) Project characterization programs at those sites. Aquifer testing at the SWHC locations was performed to characterize the shallow perched aquifer, the uppermost Santa Fe Group aquifer, and the underlying bedrock aquifer.

D.2 SUMMARY OF PREVIOUS AQUIFER TEST ANALYSIS AND RESULTS

Numerous aquifer tests have been conducted in wells in and around Sandia National Laboratories/New Mexico (SNL)/KAFB area. Wells have been tested in most of the geologic units discussed in Sections 3.1 and 3.2. A detailed discussion of the different geologic units found beneath the SNL/KAFB area is presented in Sections 3.1 and 3.2. Table D-1 summarizes the calculated hydraulic conductivities from previous aquifer tests for each geologic unit.

Table D-1. Summary of Hydraulic Values From Previous Investigations

Data source[a]	Data type	Hydraulic Conductivity (ft/day)
Santa Fe Group Ancestral Rio Grande Facies		
KAFB Installation Restoration Program (IRP) Investigation (USGS 1993)	slug test analysis (KAFB IRP monitoring wells in fluvial facies)	0.2 - 10.5
Water supply well analysis (GMI 1988a, GMI 1988b)	pumping test analyses (Yale and Burton well fields)	12.0 to 121.5
Santa Fe Group Alluvial Fan Facies		
KAFB IRP Investigation (USGS 1993)	slug test analyses	0.08 - 13.0
Water supply well analysis (GMI 1988c)	pumping test analyses (Ridgecrest well field)	9.66 to 44.7
Chemical Waste Landfill	1990 pumping test at MW-2A	0.39
Chemical Waste Landfill	1990 laboratory analysis of samples from MW-4	0.01 to 10.8
Chemical Waste Landfill	1985 slug tests at MW-1, MW-2, and MW-3	0.07 to 0.09
Chemical Waste Landfill	1994 slug tests at BW-3, BW-4, and BW-4A	0.014 to 0.031
Mixed Waste Landfill	1994 pumping test in MW-4 Upper	0.072
Mixed Waste Landfill	1994 pumping test in MW-4 Lower	1.48
Mixed Waste Landfill	Recovery data from water sampling operations (MW-1, MW-2, MW-3, and BW-1)	0.001 - 0.055
Site-Wide Hydrogeologic Characterization Project	1994 Pumping test at SFR-3P (HR-2)	10.34
Santa Fe Group Perched Aquifer Facies		
KAFB IRP Investigation (USGS 1993)	slug test analysis (KAFB IRP monitoring well KAFB-0310)	34.9
Bedrock		
Transportation and Safety Division TSA-1 (Geohydrology Associates 1987)	pumping test	1.70 - 2.22 (fractured granite, quartzite, schist, and metamorphosed sedimentary rock)
ITRI Facility Investigation (PRC 1990, PRC 1993)	pneumatic slug test	6.24 - 147.1 (shallow alluvium)

[a] Unless parenthetically noted, aquifer test results were obtained from studies conducted by the SNL/ER Project.

D.3 TEST EQUIPMENT

The test equipment that was used during aquifer testing included (1) a Digitronics Sixnet data acquisition system, (2) Campbell Scientific and Geoguard T.U.B.E.R.™ data loggers, (3) pressure transducers, (4) flow meters, (5) submersible pumps, and (6) manual water level measurement instruments. Figure D-1 shows a schematic of a typical pumping test installation.

The Digitronics Sixnet data acquisition system consists of an Iomux module with a 32-channel analog input multiplexer connected via a network board to an IBM-compatible computer. The data stream is linked to an Excel spreadsheet by means of Dynamic Data Exchange (DDE). Real time data display and analysis are performed in an Excel spreadsheet. Besides being stored in an Excel spreadsheet, the data are also written to an ASCII format file. If the computer is off or the network link is broken, the data are stored in the internal memory of the Iomux module; when the link to the computer is restored, the data stored in the Iomux module are appended to the data files in the computer. This system was used as the primary data acquisition system for testing at all the test sites.

Campbell Scientific and Geoguard T.U.B.E.R.™ data loggers are stand-alone units with built-in memory. All data recorded by these loggers are stored in internal memory until they are downloaded to a transfer module. The data are then downloaded directly from the data logger to a computer for permanent storage, plotting, and analysis. Campbell Scientific and Geoguard T.U.B.E.R.™ data loggers were used as the primary data acquisition system for wells in remote locations.

Strain gauge pressure transducers or strain gauge pressure transmitters were used to measure changes in water level. All the pressure transducers used except the Geoguard T.U.B.E.R.™ had a pressure rating from 0 to 10 pounds per square inch gauge (psig). The Geoguard T.U.B.E.R.™ transducer had a pressure rating from 0 to 28 psig. The specified accuracy of the pressure transducers is 0.1% of the rated full-scale pressure. The accuracy of all pressure transducers were pressure checked before being installed in the wells.

An Edgerton, Germeshausen and Grier, Inc. (EG&G) FT-10 turbine flow meter and flow computer were used to measure flow rates during the pumping tests. The rated range for this flow meter is 0.3 to 15 gpm with an accuracy of 0.5% of the full-scale flow rate. The flow computer displays both flow rate and total volume, and also provides an analog output, proportional to the flow rate, to the data acquisition system. When pumping rates exceeded 15 gpm, flow was measured using a volumetrically calibrated container and stop watch.

Submersible electric pumps were used in all the tests except for the test conducted in PL-3. A 5-horsepower (hp) pump capable of flow rates up to 25 gpm was used in the tests conducted at PL-2 and MRN-1. A 0.75-hp pump capable of flow rates up to 5 gpm was used in the tests conducted at TJA-2 and TRN-1. A Bennett pump capable of flow rates of 1 gpm was used in the test conducted at PL-3.

Solinst water level tapes were used to measure the depths to water prior to installing pressure transducers or transmitters, and to periodically measure the water levels after the installation of the pressure transducers, to ensure proper operation of the transducers. Solinst water level tapes have 0.01 ft graduations. Some error is introduced in picking the point at which the probe contacts the water but the element of error generally does not vary by more than 0.01 ft. This error is well within acceptable limits for the purposes of the aquifer tests.

D.4 SLUG TESTS

Between October 24, 1994 and February 16, 1995, slug tests were conducted on 11 monitoring wells in the SNL/KAFB area. The slug test method involves causing a sudden change in head in a well and measuring the water level response within that well. Head change was induced by either rapidly submerging a mechanical "slug" below water level (falling head test) or removing a slug from below the water level (rising head test). Once the mechanical slug is submerged or removed, the water within the well will then either fall or rise an amount equal to the volume of the mechanical slug. A pressure transducer linked to an electronic data logger was used to measure and record the change in water level with time in response to the slug submergence or removal.

The accuracy of hydraulic conductivity estimates using slug test data are dependent on well efficiency. Well efficiency is the ratio of the actual rate at which water will enter a well for a given drawdown divided by the maximum theoretical rate for that same drawdown. Since drilling and well completion may lead to the development of a lower permeability region near the borehole wall, well efficiency is typically reduced. Therefore, the hydraulic conductivity estimated from slug test data may be lower than the actual formation hydraulic conductivity.

The Bouwer and Rice Method (Bouwer and Rice 1976) was the analytical procedure used to analyze the data collected from each well. Hydraulic conductivities ranged from 0.04 to 19.3 ft/day. The calculated hydraulic conductivities for each well test are presented in Table D-2.

Table D-2. Summary of Hydraulic Conductivities Calculated From Slug Test Data

		Hydraulic Conductivity			
		Slug Injection Test	Slug Withdrawal Test	Average	
Monitoring Well	Aquifer Unit	ft/min	ft/min	ft/min	ft/day
TJA-2	Upper Santa Fe	7.80×10^{-3}	1.89×10^{-2}	1.34×10^{-2}	19.3
TRN-1	Abo	2.51×10^{-3}	2.50×10^{-3}	2.51×10^{-3}	3.61
KAFB-0311	Upper Santa Fe	4.27×10^{-3}	Not Analyzed	4.27×10^{-3}	6.15
MRN-1	Upper Santa Fe	1.01×10^{-4}	1.78×10^{-4}	1.40×10^{-4}	0.20
MRN-2	Upper Santa Fe	Not Analyzed	5.60×10^{-3}	5.60×10^{-3}	8.06
PL-2	Upper Santa Fe	1.83×10^{-3}	1.71×10^{-3}	1.77×10^{-3}	2.45
PL-3	Upper Santa Fe	Not Analyzed	5.84×10^{-4}	5.84×10^{-4}	0.84
TA5-MW01	Upper Santa Fe	8.52×10^{-4}	1.02×10^{-3}	9.36×10^{-4}	1.35
TA5-MW02	Upper Santa Fe	8.66×10^{-5}	7.37×10^{-5}	8.02×10^{-5}	0.12
LWDS-MW01	Upper Santa Fe	2.62×10^{-5}	Not Tested	2.62×10^{-5}	0.04
LWDS-MW02	Upper Santa Fe	1.43×10^{-3}	1.86×10^{-3}	1.65×10^{-3}	2.38

D.5 AQUIFER TESTS

Between June and September 1995, constant-rate pumping tests were conducted on five monitoring wells in the SNL/KAFB area. The wells tested were: TJA-2, TRN-1, MRN-1, PL-2, and PL-3. The well locations are shown in Plate II. Geological context of the five wells is provided by cross-section figures in Attachment 1 to this 1995 annual report:

- TJA-2 is located 15 ft east of the KAFB-0311 well, which appears in Figures 3.1-14 and 3.1-20.
- TRN-1 appears schematically in Figure 3.2-3.
- MRN-1 appears in Figures 3.1-17 and 3.1-19.
- PL-2 and PL-3 are located 20 ft and 40 ft northwest, respectively, of PL-1, which appears in Figures 3.1-16 and 3.1-19.

Additionally, LOGGER plots are available for four of the five wells, TJA-2, TRN-1, MRN-1, and PL-2, in Appendix A of Attachment 1.

D.5.1 Aquifer Test Analysis Methodology

The drawdown and recovery data were analyzed using the Cooper and Jacob straight-line method (Cooper and Jacob 1946). This method is an approximation of the Theis (1935) solution and therefore the aquifer must conform to the assumptions of the Theis (1935) conceptual model. The assumptions of the Theis (1935) conceptual model are:

1. The aquifer is homogenous and isotropic.
2. The formation has uniform thickness.
3. The formation receives no recharge from any source.
4. The pumped well penetrates and receives water from the full thickness of the water-bearing formation.
5. The aquifer is infinite in areal extent.
6. The water removed from storage is discharged instantaneously with lowering of the head.

Although most aquifers do not conform to all the theoretical conditions assumed by Theis (1935) and Cooper and Jacob (1946), results from the application of these equations and their graphic relationships are satisfactory for the purposes of this hydrogeologic study. Other more laborious methods of analysis were considered, but any additional accuracy that they might provide would not be significant.

Using the straight-line method, aquifer properties can be determined from a semilog plot of drawdown vs. time. The procedure used is as follows:

1. Plot drawdown(s) vs. log of time.
2. Fit a straight line to the data. Points where time is very small are ignored because method is invalid for very small time values.
3. For the fitted line, compute the change in drawdown for one log cycle.
4. Compute transmissivity T using

$$T = \frac{246Q}{s}$$

where

T = transmissivity in gallons per feet per day
Q = discharge rate in gpm
s = change in drawdown in feet occurring over one log cycle

5. Extend the line to obtain the value of time at zero drawdown, t_0. Compute S using

$$S = \frac{0.3Tt_0}{r^2}$$

where

S = storativity (dimensionless)
T = transmissivity in gallons per feet per day
t_0 = the value of time at zero drawdown in days
r = the distance between the pumping well and observation well in feet

The estimation of storativity depends on water level data collected from at least one observation well during a pumping test and cannot be determined from a single well test.

D.5.2 TJA-2 Pumping Test

On June 13, 1995, a 72-hr aquifer pumping test was begun on monitoring well TJA-2. Monitoring well KAFB-0311 was used as the observation well and is located 15 ft west of monitoring well TJA-2. The locations of the monitoring wells are shown in Figure D-2. Monitoring well TJA-2 is screened in the shallow perched aquifer at a depth from 275 to 295 ft. Monitoring well KAFB-0311 is screened in the Santa Fe Group alluvial fan facies of the deeper regional aquifer at a depth from 433 to 458 ft. The well schematics for monitoring wells TJA-2 and KAFB-0311 are shown in Figure D-3. The electric submersible pump was installed at a depth of approximately 297 ft. Results from slug test data indicated that the maximum yield for monitoring well TJA-2 was above the maximum pumping rate of 5 gpm of the 3-in. diameter submersible pump used, therefore no step drawdown test was conducted. Monitoring well TJA-2 was pumped for 72 hours at an average rate of 3.95 gpm. A total of 17,070 gal. were pumped. The measured water levels for monitoring wells TJA-2 and KAFB-0311 before, during, and after the test are shown in Figure D-4.

Figure D-5 shows the drawdown data for TJA-2 along with the straight-line fit and the values which were used to calculate transmissivity and hydraulic conductivity. From Figure D-5, it can be seen that the slope of the drawdown curve increased after approximately 600 min of pumping. Although the flow rate had steadily increased from 3.7 to 4.1 gpm (a 10% increase) over this period of time, it does not account for the nearly 300% increase in slope. The increased rate in drawdown represents a negative boundary effect as the cone of depression intersects a less permeable part of the aquifer. The resulting estimate for hydraulic conductivity for the initial slope is 50.2 ft/day. The estimated hydraulic conductivity for the second slope is 17.6 ft/day. The results of the test conducted in TJA-2 indicate that the shallow perched aquifer may be limited in extent. Water levels in monitoring well KAFB-0311 did not show any response to the pumping of TJA-2. The estimation of storativity was not possible because there were no observation wells screened in the shallow perched aquifer.

D.5.3 TRN-1 Pumping Test

On July 10, 1995, a 48-hr aquifer pumping test was begun on monitoring well TRN-1. The locations of the monitoring wells are shown in Figure D-6. Monitoring wells KAFB-1901 and Lake Christian West were used as the observation wells and are located approximately 2000 and 1800 ft north of monitoring well TRN-1, respectively. Monitoring well TRN-1 is screened in the Abo Formation at a depth from 320 to 340 ft. Monitoring wells KAFB-1901 and Lake Christian West are screened in the alluvium just above the Abo Formation at depths from 104 to 114 ft and 60 to 72 ft, respectively. The well schematic for monitoring well TRN-1 is shown in Figure D-7. The electric submersible pump was installed at a depth of approximately 126 ft. Results from step drawdown test data indicated that a pumping rate of 5 gpm would sufficiently stress the aquifer and provide data suitable for analysis. Monitoring well TRN-1 was pumped for 48 hr at an average rate of 4.76 gpm. A total of 13,696 gal. were pumped. The change in water level for monitoring well TRN-1 before, during, and after the test is shown in Figure D-8.

Figure D-9 shows the drawdown data for TRN-1 along with the straight-line fit and the values which were used to calculate transmissivity and hydraulic conductivity. The resulting estimate for conductivity is 0.16 ft/day. The water level in the pumping well stabilized after approximately 100 min into the pumping test, after which time a negligible amount of drawdown was observed. Water levels in the observation wells did not show any response to the pumping of TRN-1. The estimation of storativity was not possible because there was no response in the observation wells.

D.5.4 MRN-1 Pumping Test

On September 19, 1995, a 48-hr aquifer pumping test was begun on monitoring well MRN-1. Monitoring well MRN-2 was used as the observation well and is located 25 ft west of monitoring well MRN-1. The locations of the monitoring wells are shown in Figure D-10. Monitoring well MRN-1 is screened in the Santa Fe Group ancestral Rio Grande facies at a depth from 546.7 to 586.7 ft. Monitoring well MRN-2 is also screened in the Santa Fe Group ancestral Rio Grande facies at a depth from 410 to 440 ft. The well schematics for monitoring wells MRN-1 and MRN-2 are shown in Figure D-11. An electric submersible pump was installed at a depth of approximately 499 ft. Monitoring well MRN-1 was pumped for 48 hr at an average rate of 22.83 gpm. A total of 65,574 gal. were pumped. The water levels in monitoring wells MRN-1 and MRN-2 before, during, and after the test are shown in Figure D-12.

Hydraulic conductivities were determined using the Cooper-Jacob (1946) method (Figure D-13). Both early time and late time drawdown data were analyzed. The early time drawdown data (3 to 60 minutes, straight-line fit #2) resulted in a steeper slope and yielded a hydraulic conductivity of 26 ft/day. The late time data (20 to 3000 minutes, straight-line fit #1) yielded a higher hydraulic conductivity of 47 ft/day. The hydraulic conductivity was high enough to indicate that MRN-1 could sustain yields much greater than its tested pumping rate. Water levels in observation well MRN-2 did not show any response to the pumping of MRN-1. The estimation of storativity was not possible because of the lack of response in observation well water levels.

D.5.5 Power Line Road Pumping Tests

Two pumping tests were conducted at the Power Line Road location. The pumping test performed on monitoring well PL-2 was done to determine the hydraulic conductivity and storativity in the Upper

Santa Fe Group approximately 125 ft below the uppermost saturation. The pumping test performed on monitoring well PL-3 was done to determine the hydraulic conductivity and storativity in the uppermost 20 to 50 ft of the Santa Fe Group aquifer.

D.5.5.1 PL-2 pumping test

On September 5, 1995, a 24-hr aquifer pumping test was begun on monitoring well PL-2. Monitoring wells PL-1 and PL-3 were used as the observation wells. All three wells are screened in the Santa Fe Group ancestral Rio Grande facies. The locations of the monitoring wells are shown in Figure D-14. Monitoring well PL-2 is screened at a depth from 577 to 597 ft. Monitoring well PL-1 is located approximately 20 ft east of PL-2 and is screened at depths from 440 to 470 ft. Monitoring well PL-3 is located approximately 20 ft west of PL-2 and is screened at depths from 445 to 465 ft. The well schematics for monitoring wells PL-1, PL-2, and PL-3 are shown in Figure D-15. An electric submersible pump was installed at a depth of approximately 548 ft. Monitoring well PL-2 was pumped for 24 hr at an average rate of 24.83 gpm. A total of 35,763 gal. were pumped. The water levels for monitoring wells PL-1, PL-2, and PL-3 before, during, and after the test are shown in Figure D-16.

Figure D-17 shows the drawdown data for PL-2 along with the straight-line fit and the values which were used to calculate transmissivity and hydraulic conductivity. The resulting estimate for hydraulic conductivity is 147.1 ft/day. The hydraulic conductivity was high enough to indicate that PL-2 could sustain yields much greater than its tested pumping rate. Water levels in the observation wells did not show any response to the pumping of PL-2. The estimation of storativity was not possible because of the lack of response in observation well water levels.

D.5.5.2 PL-3 pumping test

On August 10, 1995, PL-3 was pumped for 450 min at an average rate of 0.92 gpm until the water level in the well was drawn below the pump intake. Monitoring wells PL-1 and PL-2 were used as the observation wells. A Bennett pump was installed at a depth of approximately 473 ft. A total of 415 gal. were pumped. The water levels for monitoring wells PL-2 and PL-3 before, during, and after the test are shown in Figure D-18. Note that the scales used for the two wells differ in Figure D-18. The apparent parallel decline of approximately 0.05 ft in well PL-2 during the 22 ft decline in well PL-3 is believed to be related to barometric pressure changes during or near the same period. The barometric pressure and its impact on the PL-2 water level data is shown on Figure D-19. Together, Figures D-18 and D-19 show:

1. The water levels in well PL-2 decline with increase in barometric pressure,
2. The water level declines in well PL-2 began before the pumping started, and
3. The water level in well PL-2 begins to rise before pumping ceases.

Figure D-20 shows the drawdown data for PL-3 along with the straight-line fit and the values which were used to calculate conductivity. The resulting estimate for conductivity is 0.16 ft/day. Water levels in the observation wells PL-1 and PL-2 did not show any response to the pumping of PL-3. The estimation of storativity was not possible because of the lack of response in observation well water levels.

D.5.6 Summary of 1995 Site-Wide Hydrogeologic Characterization Project Aquifer Tests and Results

Well testing at the five test locations provided good estimates for hydraulic conductivity in the shallow perched aquifer, the uppermost Santa Fe Group aquifer, and the underlying bedrock aquifer. Due to the lack of observation well data and/or insufficient drawdown in the observation wells, no reliable values for storativity were established at the five test locations. Table D-3 summarizes the results of the pumping tests conducted in 1995. Comparison of the slug test data analysis results from the PL-2 and MRN-1 monitoring wells to the aquifer pumping test data analysis results show that slug tests in this unit may yield data that significantly underestimate hydraulic conductivity (see Tables D-2 and D-3). One possible explanation is that the drilling mud used during the installation of these wells may have contributed to the development of a low permeability zone adjacent to the wellbore. This comparison suggests that the results of slug tests may not be representative of the true hydraulic conductivity for this unit.

D.6 CHEMICAL WASTE LANDFILL

Pumping tests were performed in monitor wells MW-2B (Lower) and BW-4A at the CWL in 1995. The pumped wells in both tests are screened in the Santa Fe Group. Details of the tests and analysis are reported in the CWL Groundwater Assessment Report (SNL/NM 1995). Estimated hydraulic conductivity and storativity values from the MW2-B (Lower) pumping test ranged from 15.8 to 27.4 ft/day and 3.3×10^{-5} to 1.7×10^{-4}, respectively. The estimated hydraulic conductivity value from the BW-4A pumping test was 0.01 ft/day. Estimation of storativity from the BW-4A pumping test was not possible due to the lack of response in observation well water levels.

Table D-3. Summary of Hydraulic Values From 1995 Pumping Tests

Monitor Well	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)
Santa Fe Group Ancestral Rio Grande Facies		
MRN-1	3499	26.0 - 47.0
PL-2	5149	147.1
PL-3	1.9	0.13
Santa Fe Group Alluvial Fan Facies		
MW-2B (lower)	620	21.6
Observation wells MW-5 (lower) and MW-6 (lower) during 1995 pumping test at MW-2B (lower)	0.018 -0.019	25.9 - 27.4
BW-4A	0.3	0.01
TA2-NW1-595	9480	14.4
Bedrock		
TRN-1	7.1	0.16
Santa Fe Group Perched Aquifer Facies		
TJA-2	1004.5	50.2

D.7 TECHNICAL AREA II MONITOR WELLS

Water levels were continuously monitored in well TA2/NW1/595 with a Campbell Scientific data logger from June to December 1995. Monitoring well TA2/NW1/595 is located along the north boundary of TA-2 and is completed with two separate screened intervals (Figure D-21). The upper screen extends from 535 to 555 ft below ground surface (bgs) surrounded by a sand pack extending from 523 to 562 ft bgs. The lower screen extends from 585 to 595 ft bgs with a sand pack from 592 to 605 ft bgs. The two screened intervals are connected by blank casing with Volclay seal in the annulus from 562 to 572 ft bgs. Both intervals are screened in the Santa Fe Group. An inflatable packer has been placed between the two screened intervals and pressure transducers have been installed to measure water level responses above and below the packer.

A review of the water level data indicates that the two intervals are completed in different water-bearing units. Water levels in the lower screened interval are influenced by pumping of production well KAFB-11 which is located 5780 ft east of TA2-NW1-595 (see Plate II). The water level in the upper interval did not show any response to pumping of KAFB-11. Figure D-22 shows the change in water levels for the lower screened interval due to the pumping of KAFB-11. The production schedule KAFB-11 corresponds directly to the drawdown and recovery in water levels in the lower screened unit of TA2-NW1-595. The drawdown data collected from TA2-NW1-595 (lower) between June 2 and June 14, 1995 were used to calculated transmissivity and storativity. During this time period, KAFB-11 was pumped at an average rate of 1545 gpm. Figure D-23 shows the drawdown data for the lower interval of TA2-NW1-595 along with the straight-line fit and the values which were used to calculate conductivity. The resulting estimate for hydraulic conductivity is 14.4 ft/day. The storage coefficient is 2.4×10^{-4}, which is in the range for a confined aquifer.

D.8 REFERENCES

Bouwer, H., and Rice, R. C., 1976. A Slug Test Method for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells, Water Resources Research, Vol. 12, No. 3, pp. 423-428.

Cooper, H. H., Jr. and C. E. Jacob, 1946. A Generalized Graphic Method for Evaluating Formation Constants and Summarizing Well-Field History, Transactions, American Geophysical Union, Vol. 27, No. 4, pp. 526-534.

Freeze, R. A., and J. A. Cherry, 1979. Groundwater, Englewood Cliffs, NJ: Prentice Hall, 604 p.

GMI, 1988a. Groundwater Management Incorporated. Pumping Test Data Analysis: Burton Well Field, City of Albuquerque, New Mexico, unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

GMI, 1988b. Groundwater Management Incorporated. Pumping Test Data Analysis: Miles Road Well Field, City of Albuquerque, New Mexico, unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

GMI, 1988c. Groundwater Management Incorporated. Pumping Test Data Analysis: Ridgecrest Well Field, City of Albuquerque, New Mexico, unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

Geohydrology Associates, Inc., 1987. Drilling Summary of the TSA Exploratory Well No. 1, unpublished report to U.S. Department of Energy, December 1987.

PRC, 1990. PRC Environmental Management, Inc. ITRI Lagoon Hydrogeological Study, unpublished report prepared for the Lovelace Inhalation Toxicology Research Institute, Albuquerque, NM.

PRC, 1993. PRC Environmental Management, Inc. Alluvial Aquifer Characterization Study, unpublished report prepared for the Lovelace Inhalation Toxicology Research Institute, Albuquerque, NM.

SNL/NM, 1995. Sandia National Laboratories/ New Mexico. Chemical Waste Landfill Ground-water Assessment Report, prepared for SNL/NM Environmental Restoration Project by INTERA Inc., Albuquerque, NM.

Theis, C. V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions of the American Geophysical Union, 16th Annual Meeting, pp. 519-524.

USGS, 1993. United States Geological Survey. Installation Restoration Program, Stage 2A, RI/FS Technical Report for Kirtland Air Force Base, USGS Water Resources Division, Albuquerque, NM.

FIGURES

Sandia National Laboratories

Site-Wide Hydrogeologic Characterization Project

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Environmental
Restoration
Project

United States Department of Energy
Albuquerque Operations Office

FIGURES

Figures and plates are located in a supplemental figure volume.

FIGURES (Continued)

FIGURES (Concluded)

PLATES

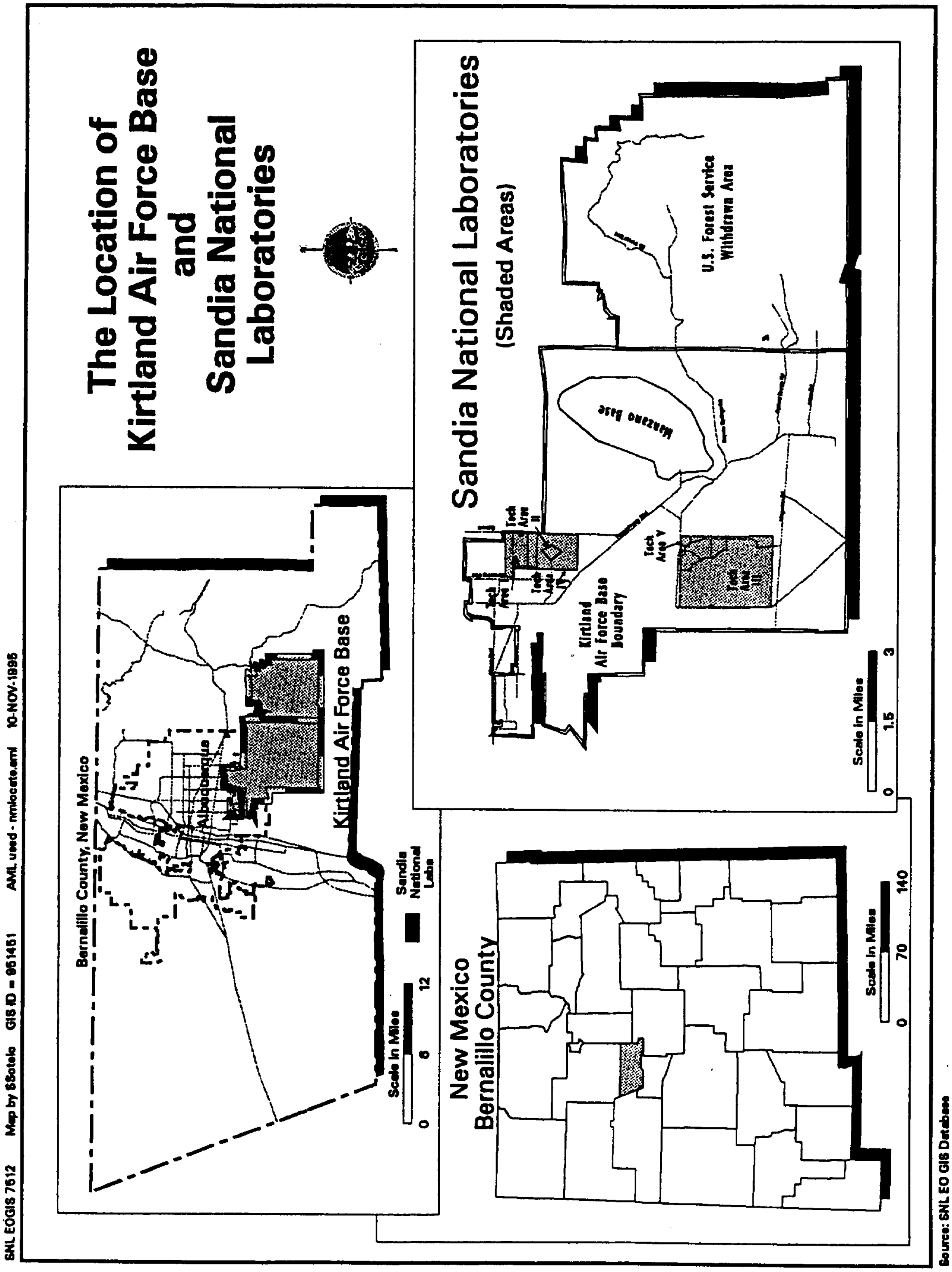


Figure 1.3-1. The Location of Kirtland Air Force Base and Sandia National Laboratories

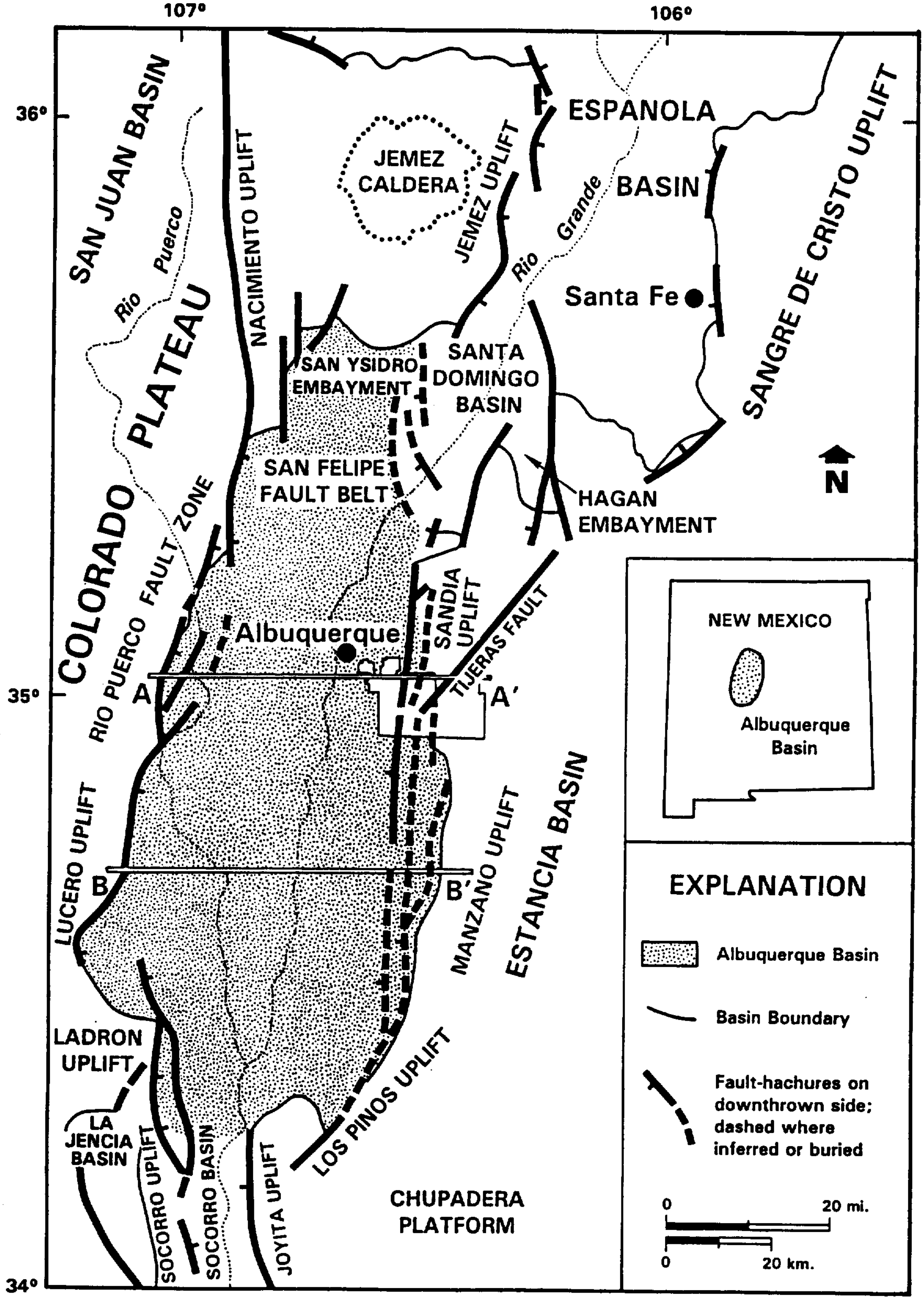


Figure 3.1.1-1. Generalized Regional Tectonic Map of the Albuquerque Basin (cross sections shown on Figure 3.1.1-2)

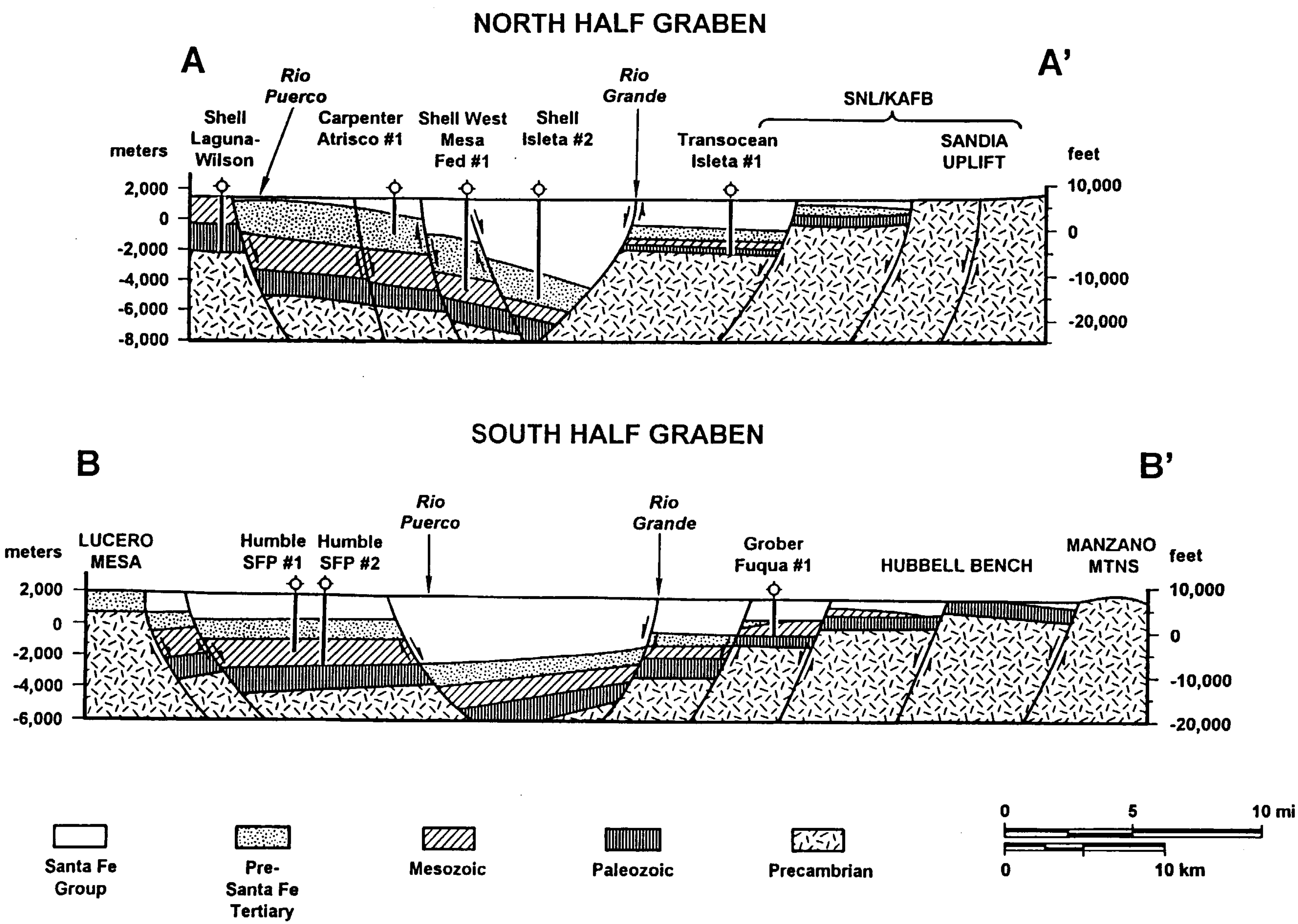


Figure 3.1.1-2. Generalized Regional Cross Sections through Albuquerque Basin (as noted on Figure 3.1.1-1)

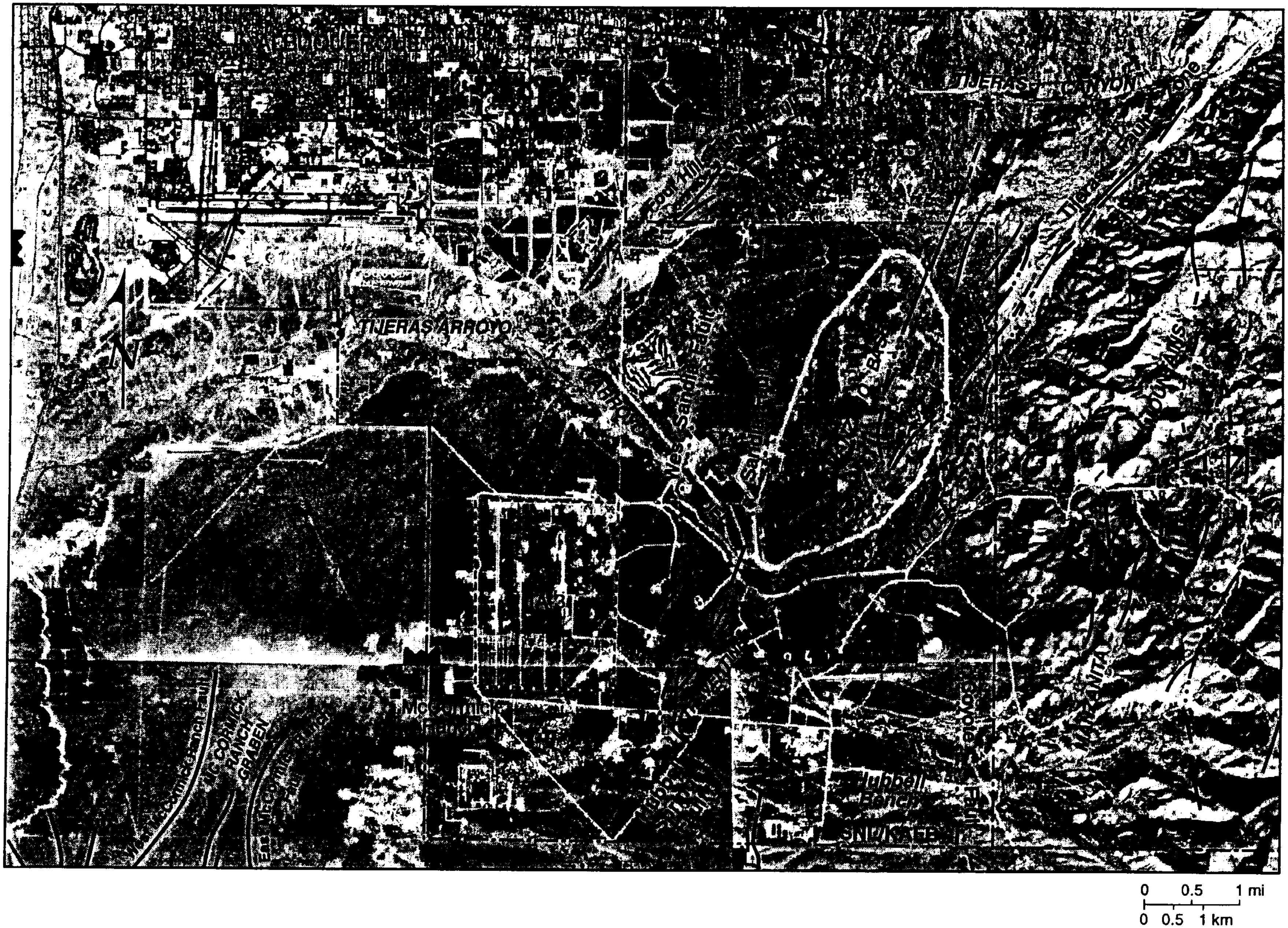


Figure 3.1.1-3. Composite Image Showing Major Faults in the Sandia National Laboratories/Kirtland Air Force Base Area. Faults within the Manzanita Mountains after Myers and McKay (1970, 1976).

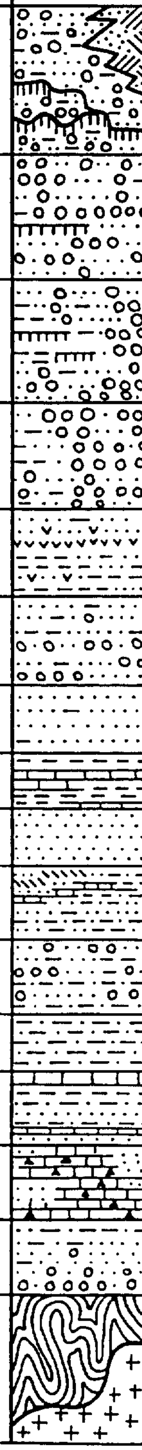
ERA	SYSTEM	SERIES	UNIT/FORMATION		STRAT. COLUMN	DESCRIPTION
CENOZOIC	QUATERNARY	Holocene to Middle Pleistocene	Surficial Units			Cross-bedded, fine- to medium-grained eolian sand Poorly-sorted silty sandy cobble to boulder gravel Poorly-sorted silty sandy cobble to boulder gravel with relict and buried soils *Unconformity*
	TERTIARY	Middle or Early Pleistocene to Pliocene	Santa Fe Group	Upper Santa Fe Unit		Basinal: coarse- to fine-grained sandstone; common buried soils Marginal: pebbles, cobbles in fine-grained matrix
		Miocene		Middle Santa Fe Unit		Basinal: medium- to fine-grained sandstone and mudstone; common buried soils Marginal; conglomeratic sandstone to pebbles and cobbles; common buried soils
				Lower Santa Fe Unit		Basinal: medium- to fine-grained sandstone, sandy mudstones Marginal: conglomeratic sandstone and mudstone *Unconformity*
		Oligocene	Unit of Isleta #2 Well			Fine- to coarse-grained sandstone; claystone, silt beds; volcanic detritus and ash-flow tuffs
		Eocene to Paleocene	Baca/ Galisteo Formations			Sandstone, variegated mudstone, and conglomerate *Unconformity*
MESOZOIC		Upper Triassic	Santa Rosa Sandstone			Buff brown sandstone, petrified wood
PALEOZOIC		Upper Permian	San Andres Formation			Gray limestone, separated by red shale *Unconformity*
			Glorieta Sandstone			Medium- to coarse-grained yellowish gray sandstone
		Lower Permian	Yeso Formation			Upper: gypsiferous sandstone, siltstone, and limestone Lower: fine-grained sandstone and siltstone
			Abo Formation			Fine- to coarse-grained sandstone and conglomerate with interbedded siltstone
			Madera Group	Bursum Fm.		Finely laminated silty mudstone
		Upper to Middle Pennsylvanian		Wild Cow Formation		Rhythmically bedded sequence: conglomerate, sandstone, siltstone, shale, and limestone
				Los Moyos Formation		Gray calcarenite with chert
		Middle Pennsylvanian	Sandia Formation			Fining-upwards clastic sequence: conglomerate to calcareous siltstone *Unconformity*
PRECAMBRIAN			Isleta Metasediments Tijeras Greenstone Complex Coyote Canyon Sequence Sandia Granite			Phyllite; meta-arkose; metaquartzite; greenstone; metarhyolite; quartzite; microcline and biotite granite

Figure 3.1.2-1. Generalized Stratigraphic Column of the Sandia National Laboratories/Kirtland Air Force Base Area

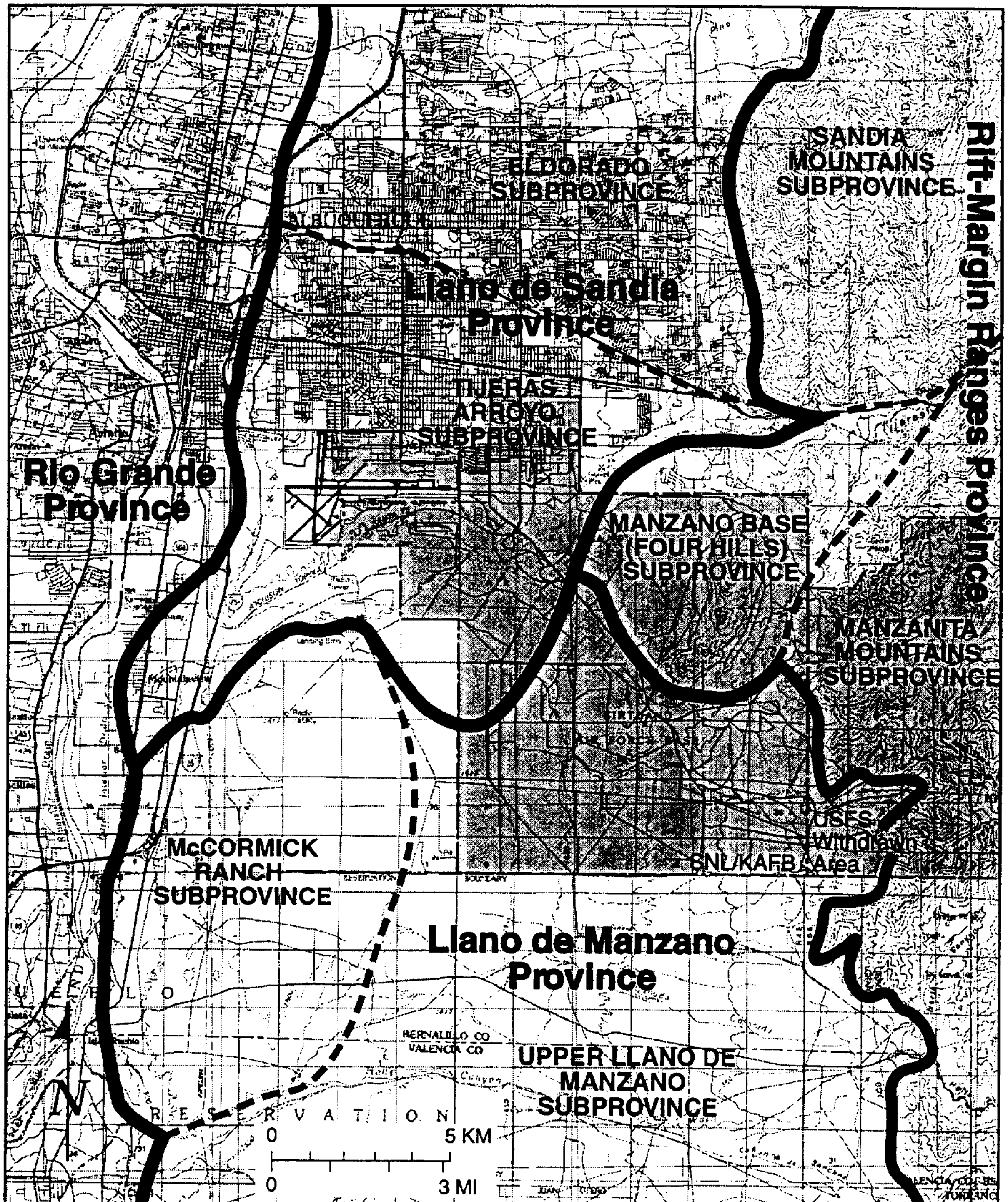


Figure 3.1.3-1. Geomorphic Provinces and Subprovinces of the Sandia National Laboratories/Kirtland Air Force Base Area

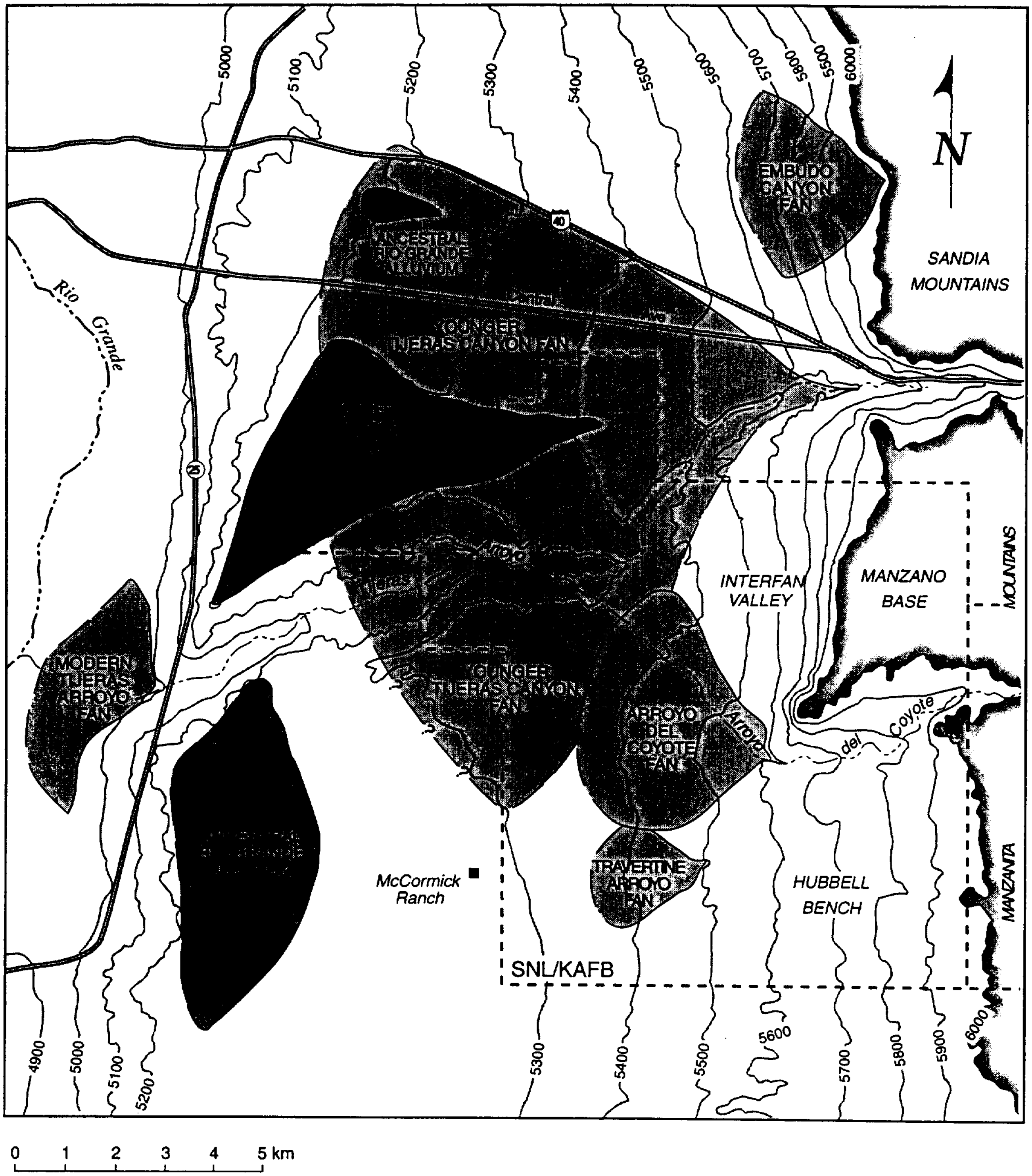


Figure 3.1.3-2. Generalized Topographic Map of the Sandia National Laboratories/Kirtland Air Force Base Area West of the Sandia and Manzanita Mountains, Showing Primary Alluvial Fans Derived from Major Drainages

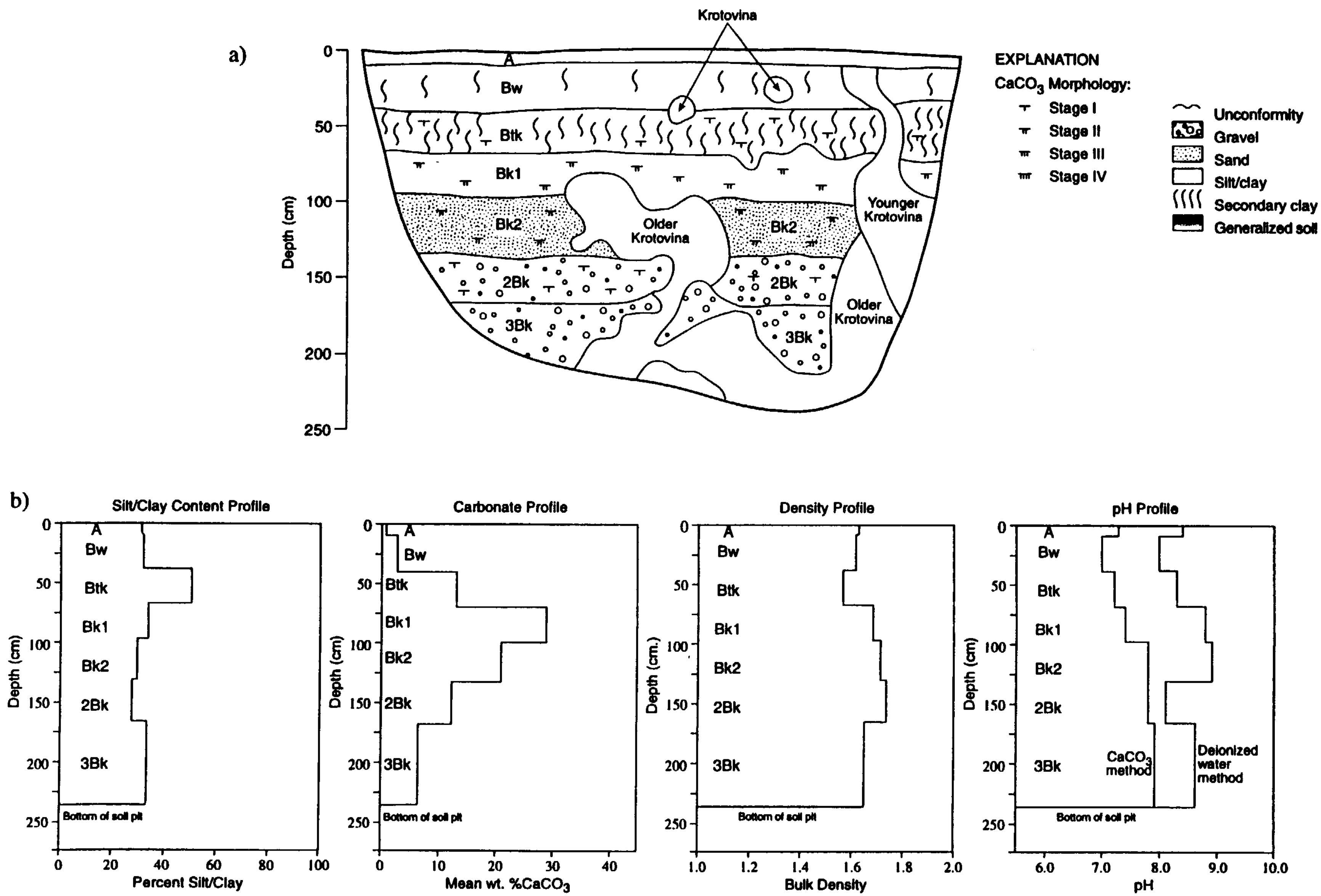


Figure 3.1.4-1. Example of Soil Profile Characteristics from (a) Field Observations and (b) Laboratory Analyses. Data from Soil Pit SP24 (Attachment 1, Appendix D).

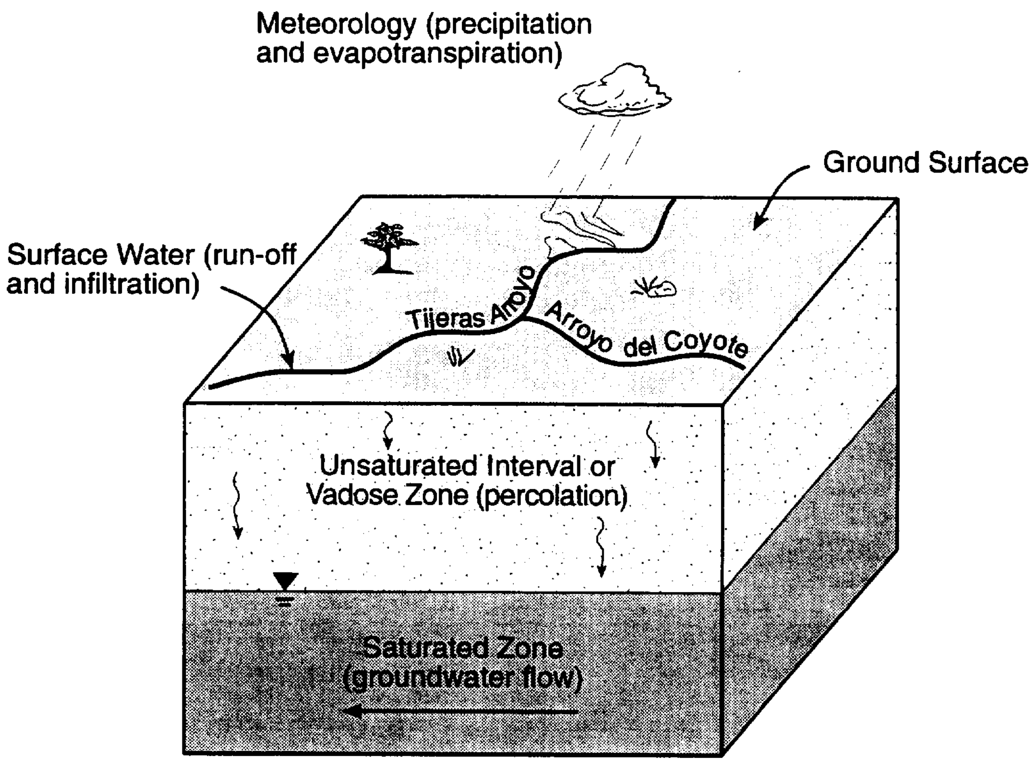


Figure 3.2-1. Hydrologic Setting and Zonation

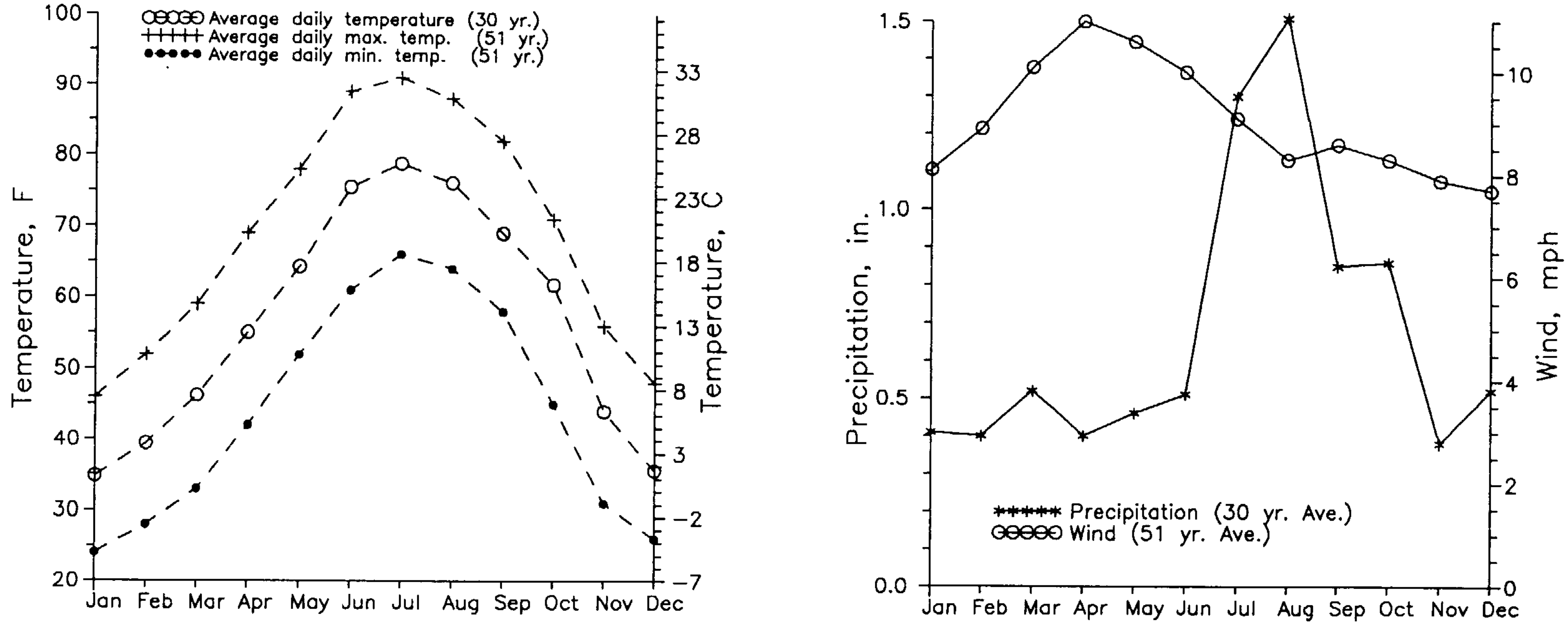


Figure 3.2.1-1. Average Monthly Temperature, Wind Speed, and Precipitation at Albuquerque International Airport

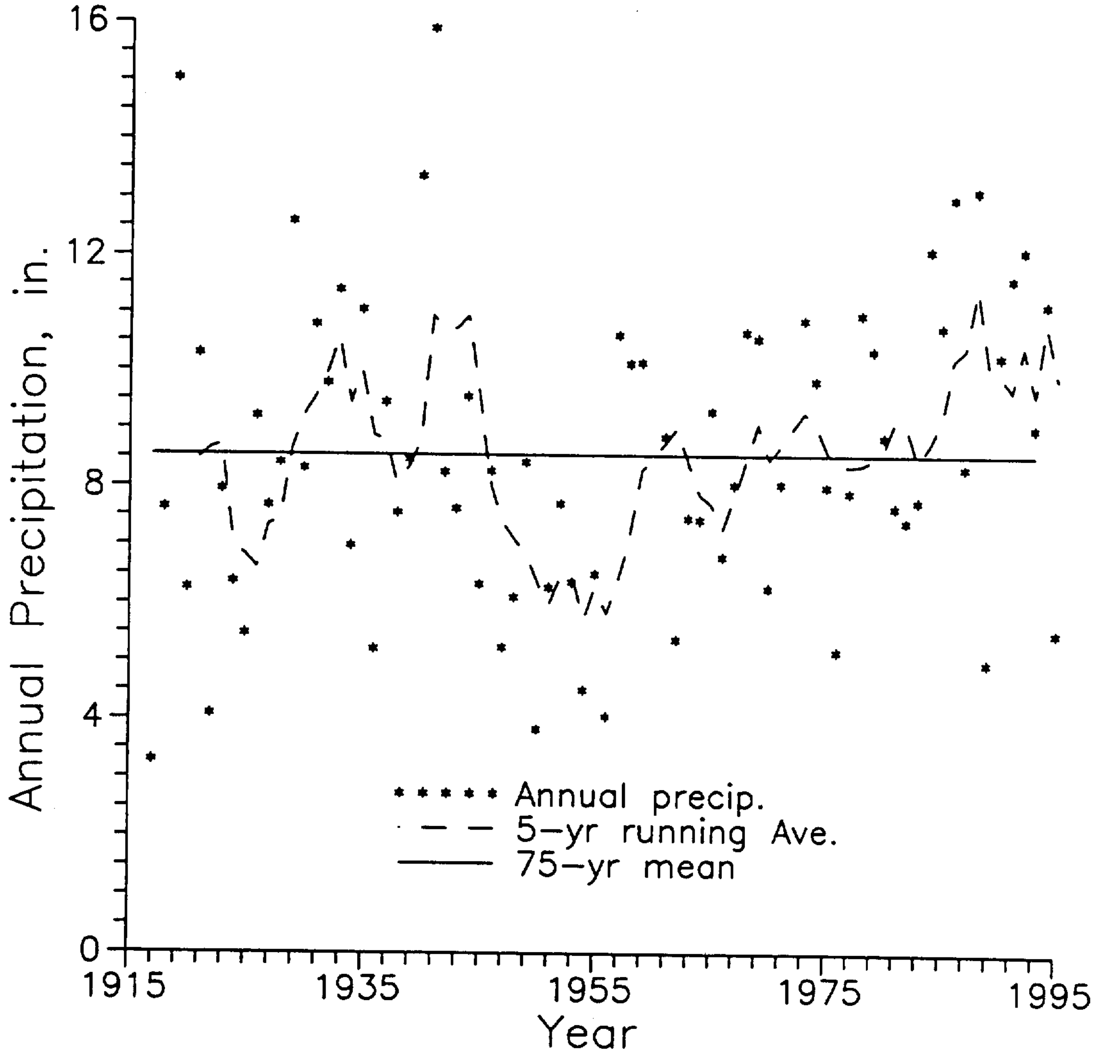


Figure 3.2.1-2. Long-Term Precipitation Data Collected at Albuquerque International Airport

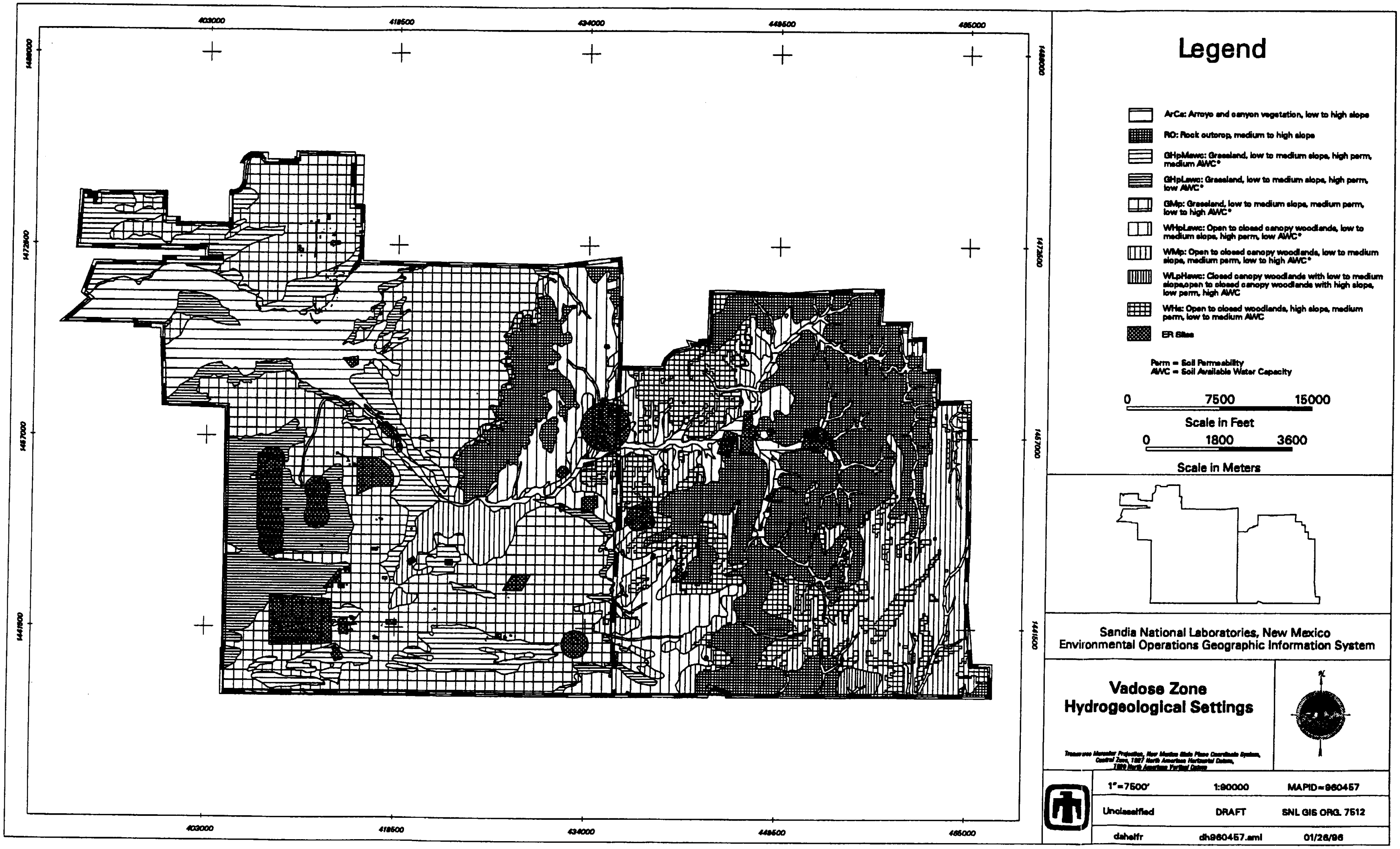


Figure 3.2.2-1. Vadose Zone Hydrogeologic Settings

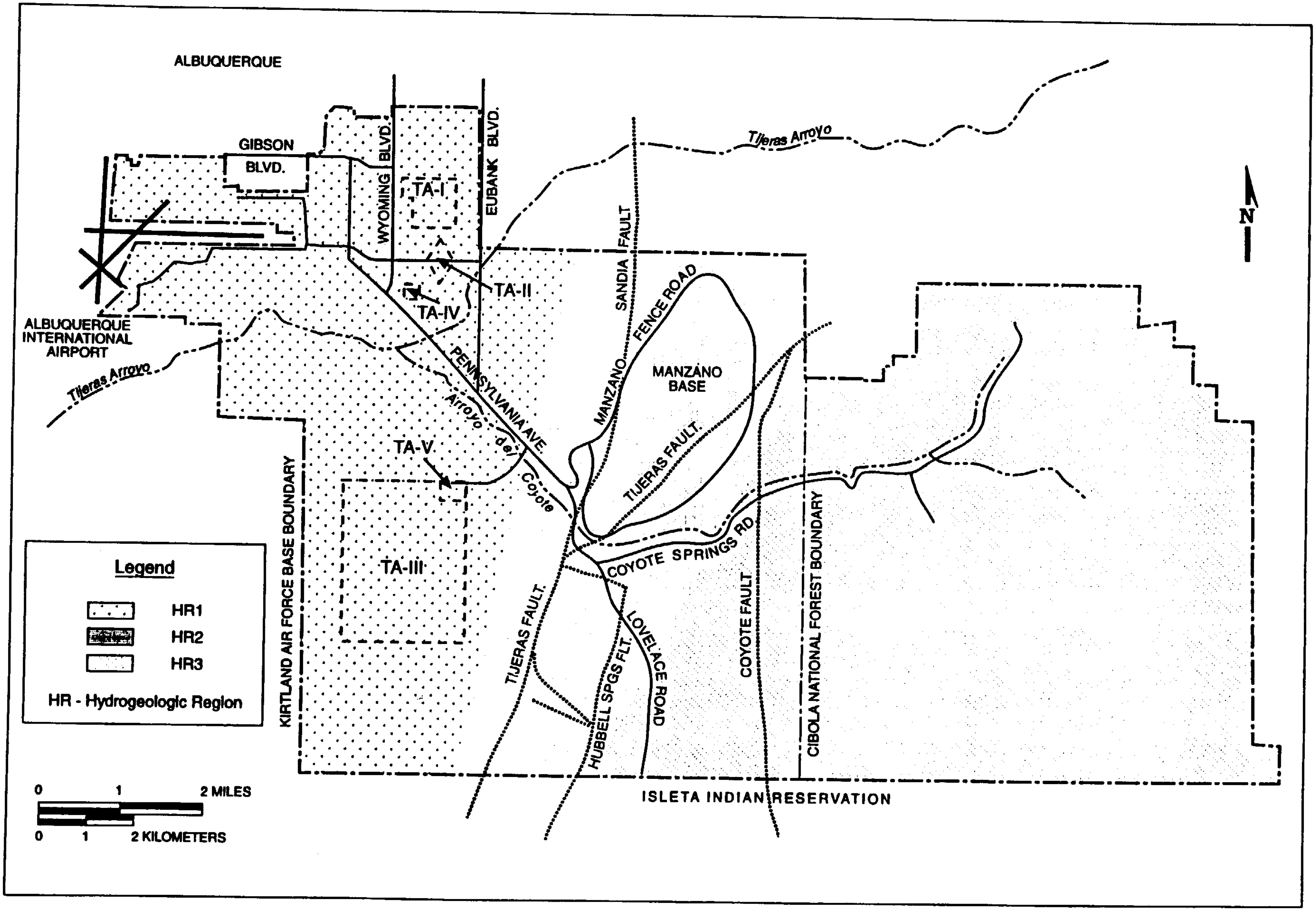


Figure 3.2.4-1. Hydrogeologic Regions Identified by Sandia National Laboratories/New Mexico (SNL/NM 1994b)

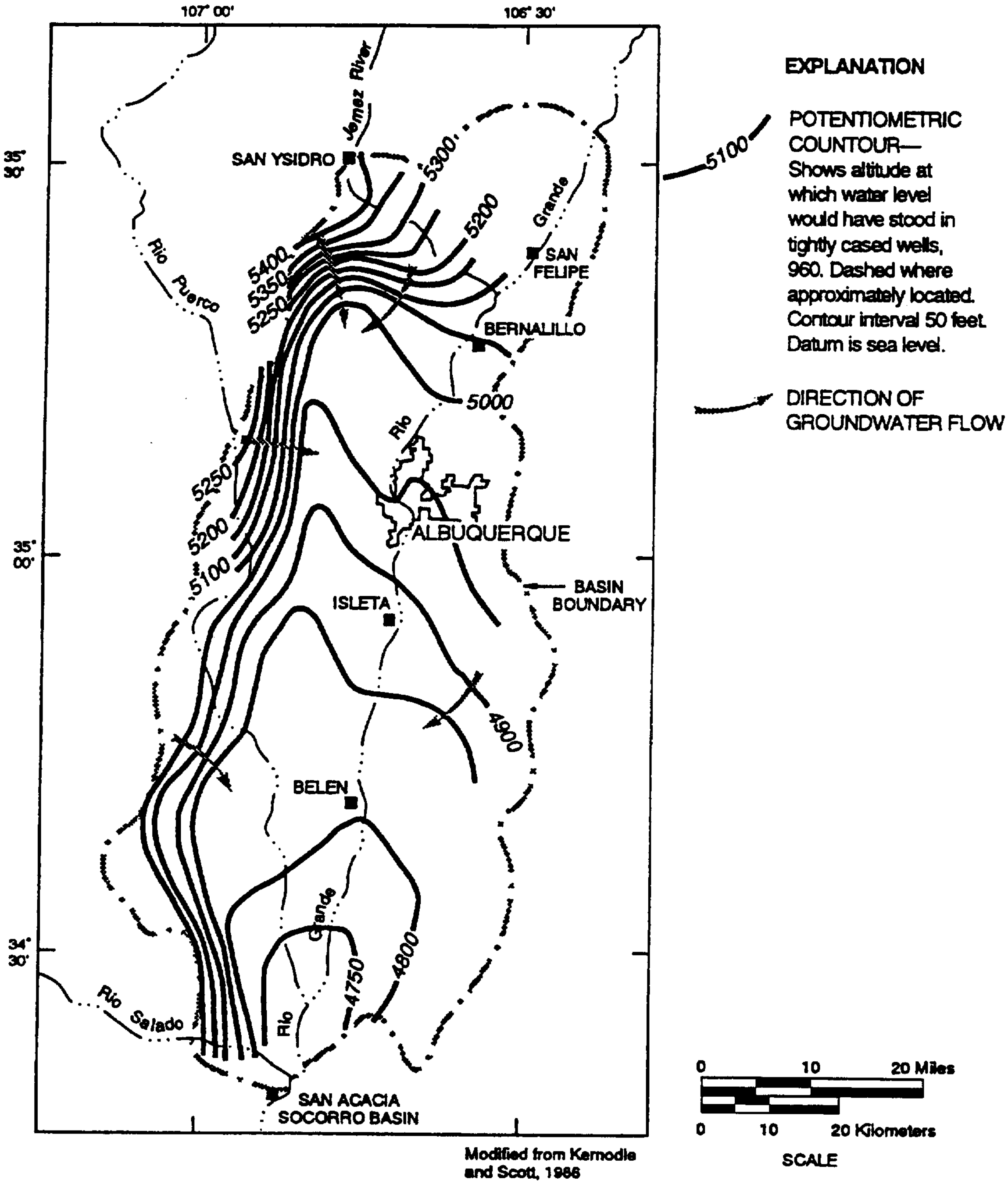


Figure 3.2.4-2. Regional Potentiometric Surface Map for the Albuquerque Basin-Fill (Santa Fe Group) Aquifer (modified from Kernodle and Scott [1986])

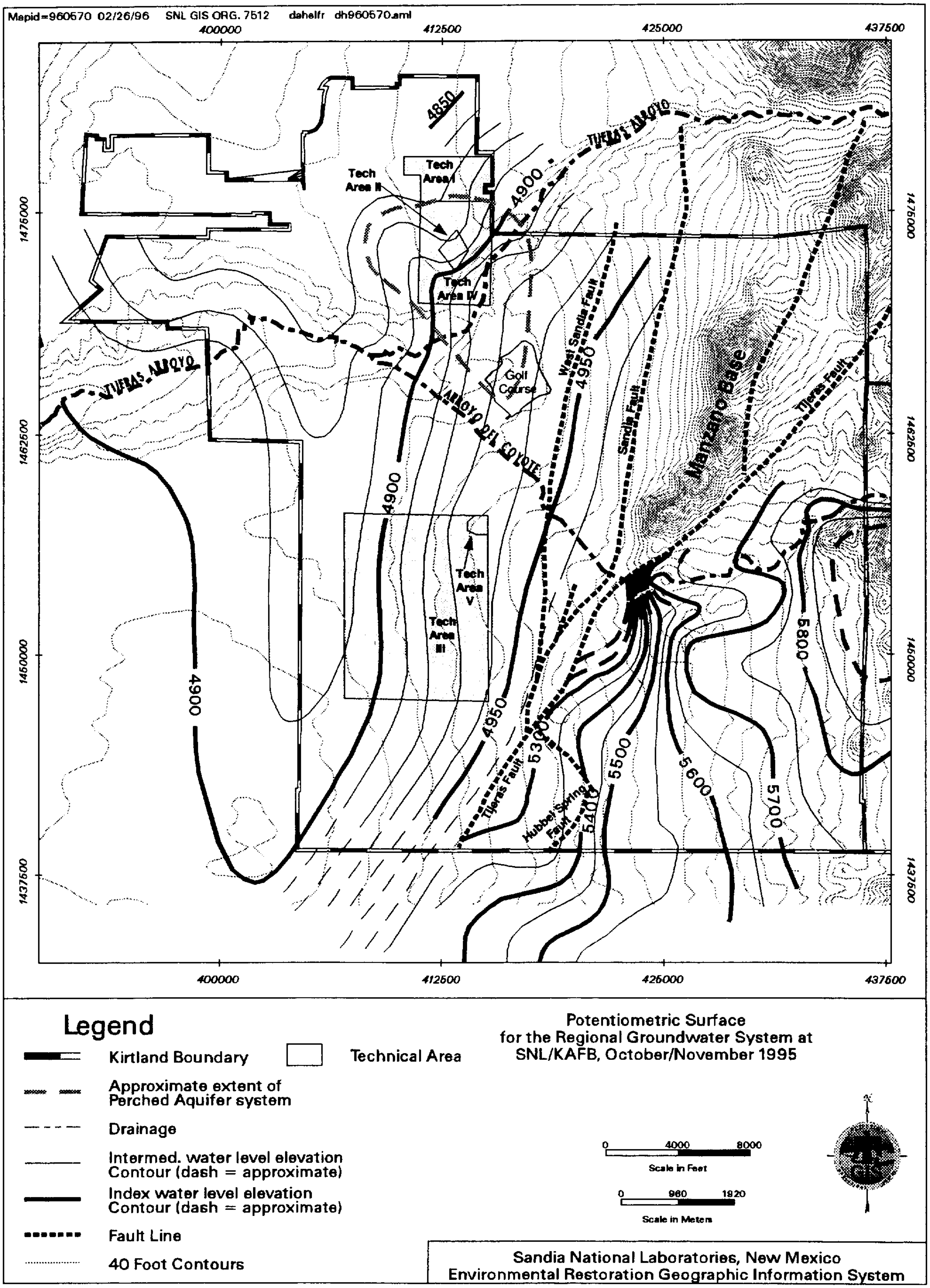


Figure 3.2.4-3. Potentiometric Surface for the Regional Groundwater System at Sandia National Laboratories/Kirtland Air Force Base, October 1995

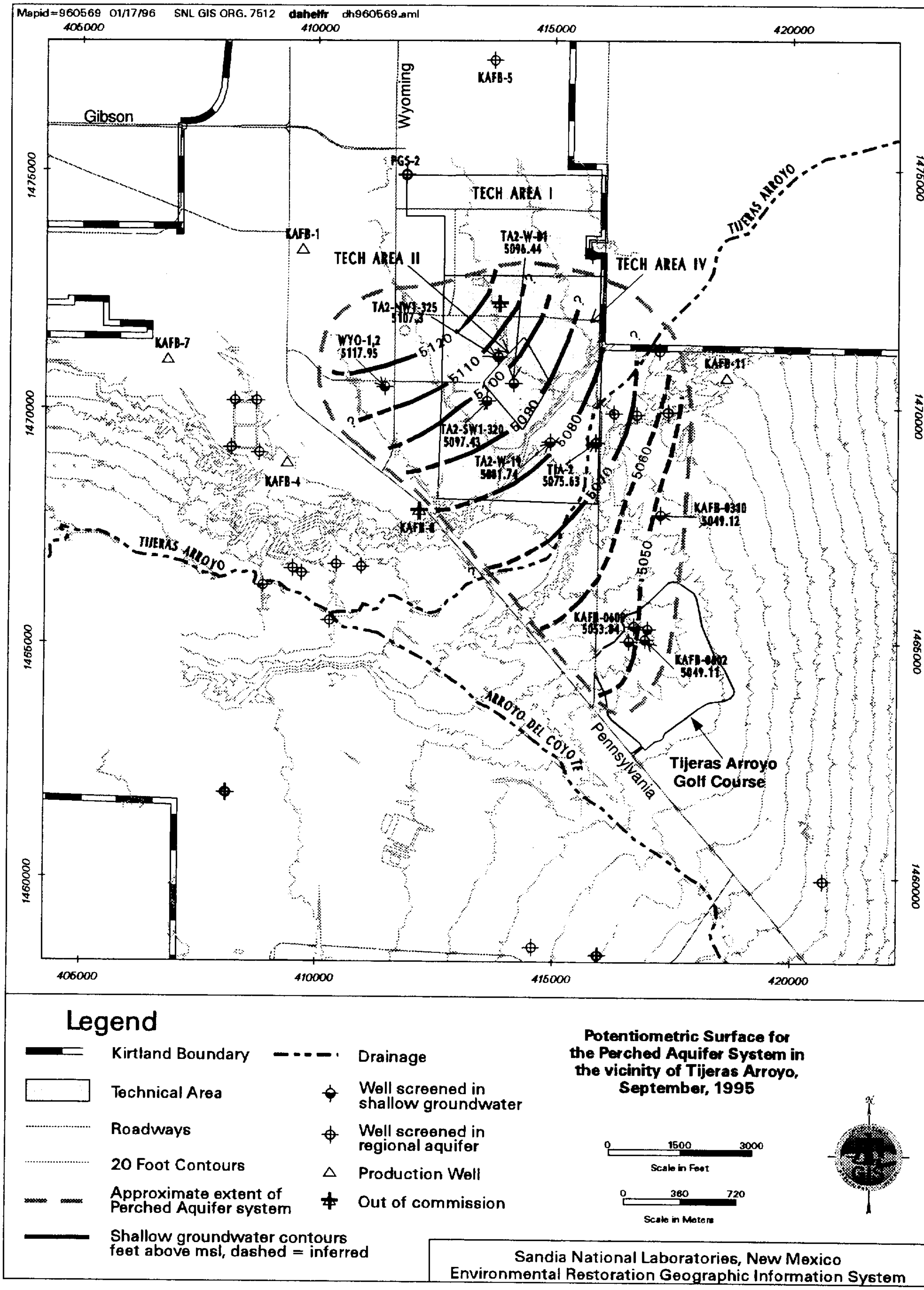


Figure 3.2.4-4. Potentiometric Surface Map for the Shallow Groundwater in the Vicinity of Tijeras Arroyo, October Through November 1995

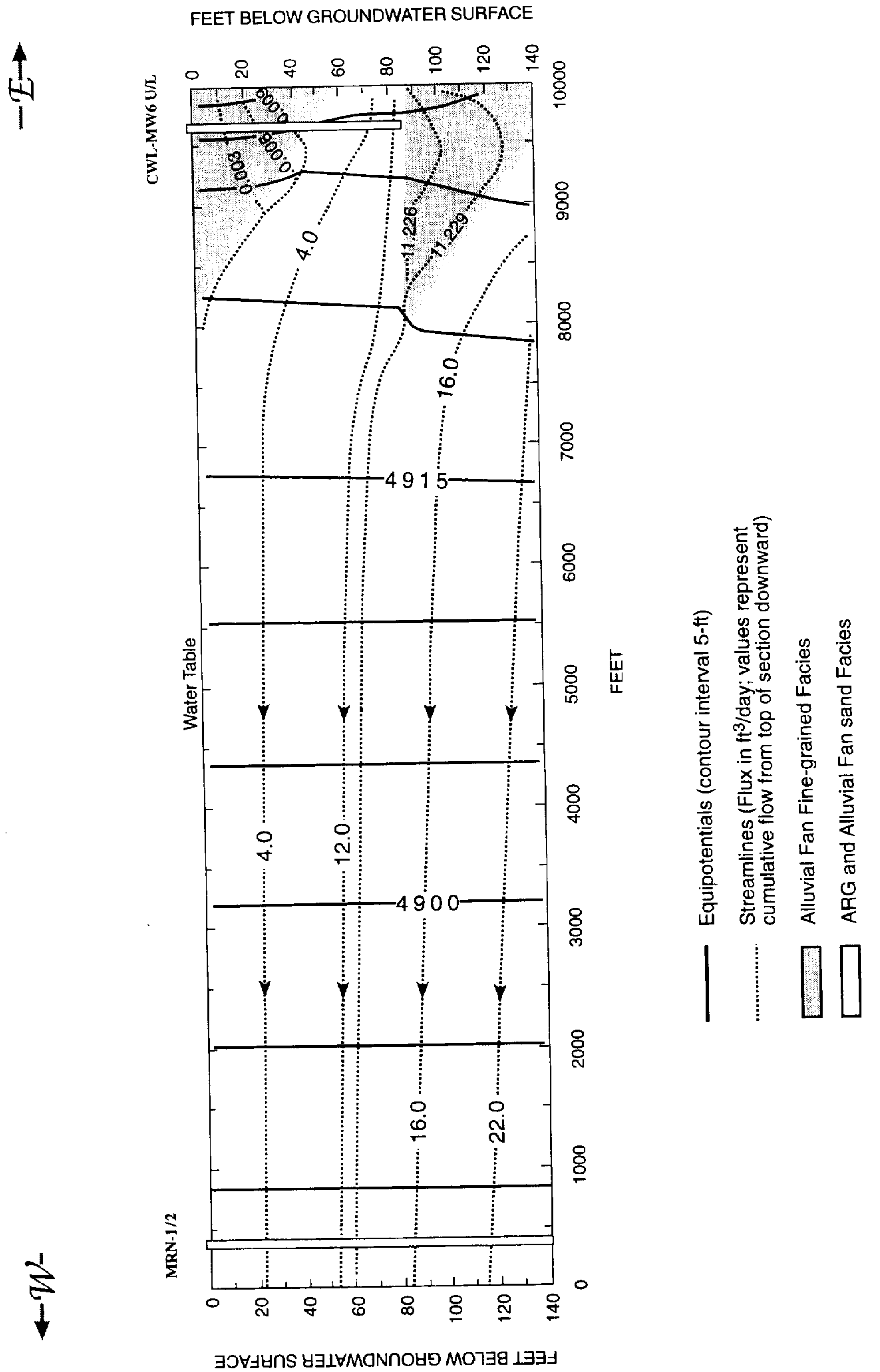


Figure 3.2.4-5. Flow Net Model Cross-Section Hydrostratigraphy

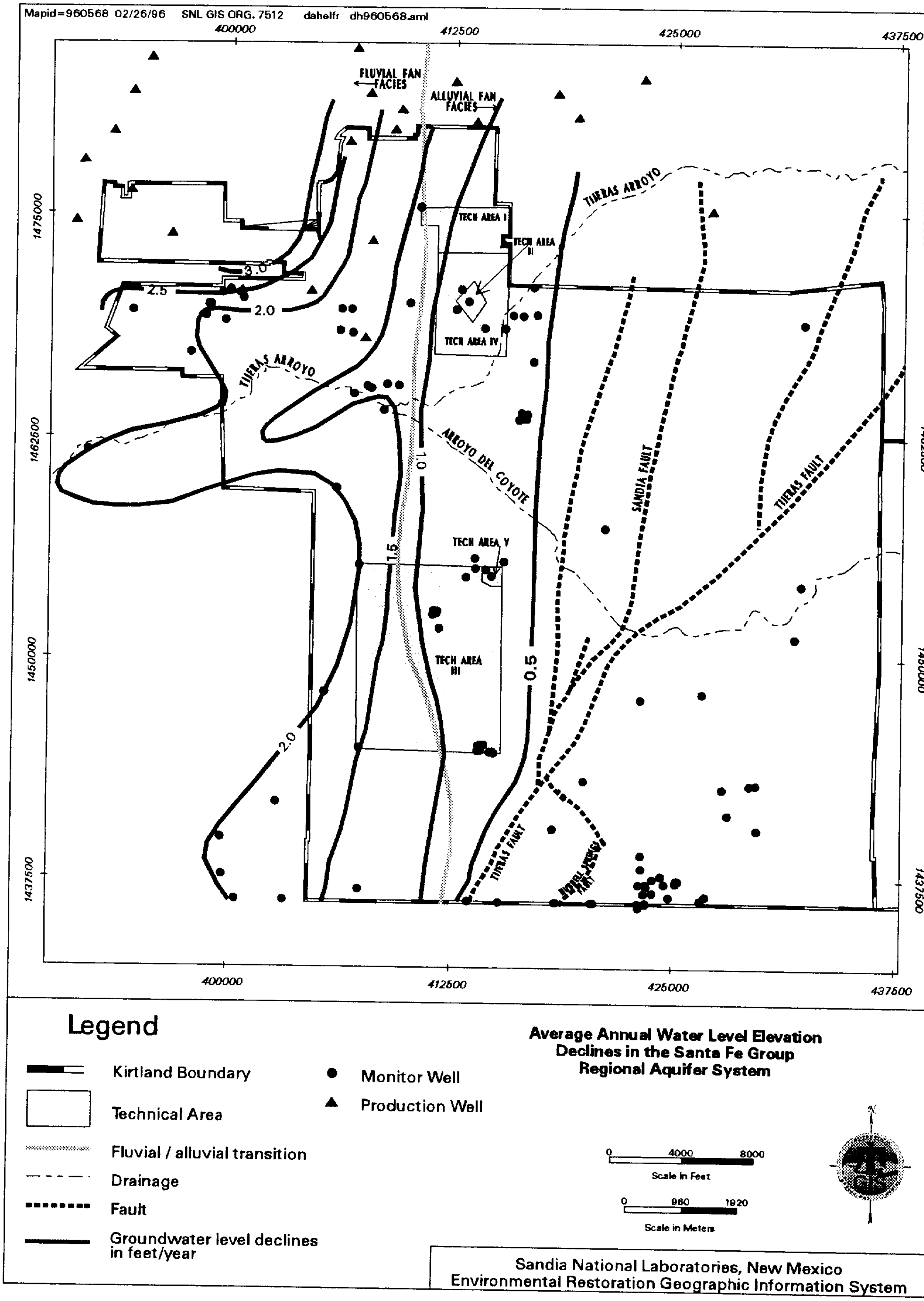


Figure 3.2.4-6. Average Annual Water Level Elevation Declines in the Santa Fe Group Regional Aquifer System

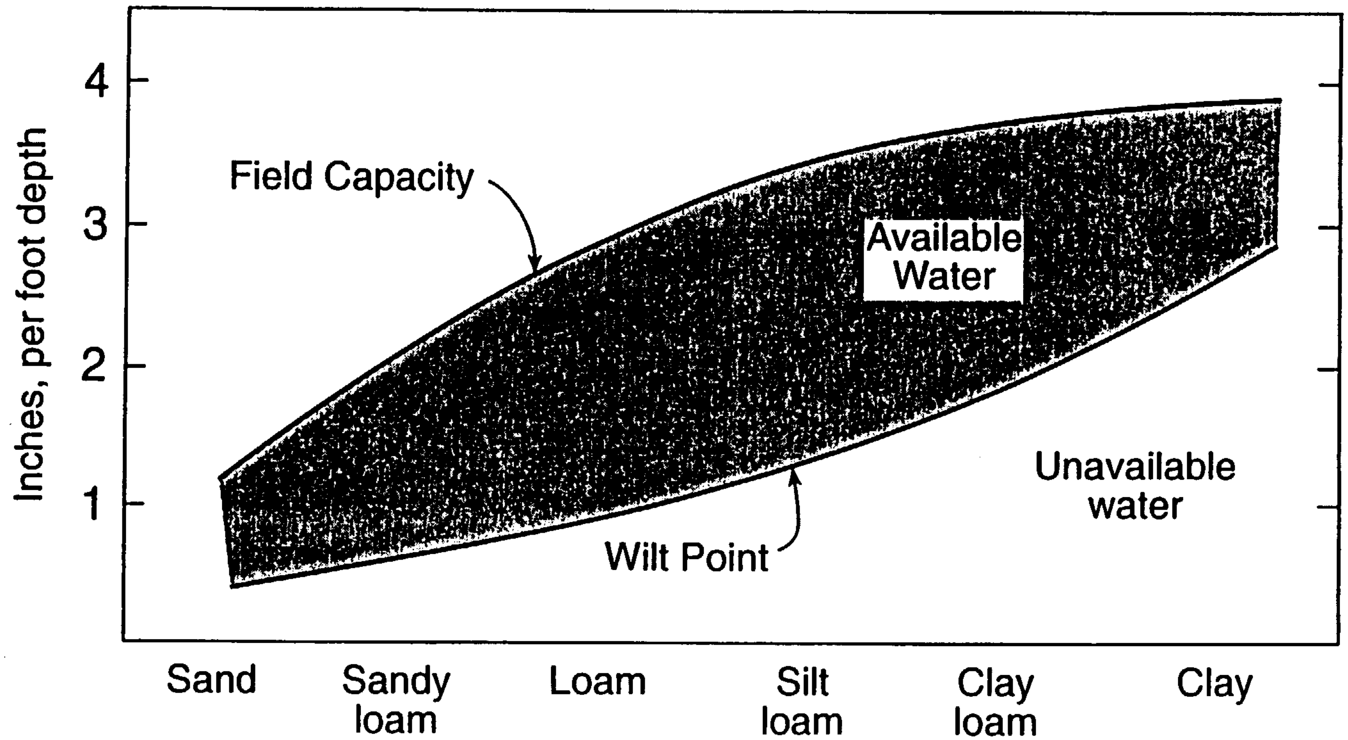


Figure 4.1.2-1. Water-Holding Capacity and Wilting Point of Various Soil Textures (adapted from USDA Yearbook of Agriculture, 1955)

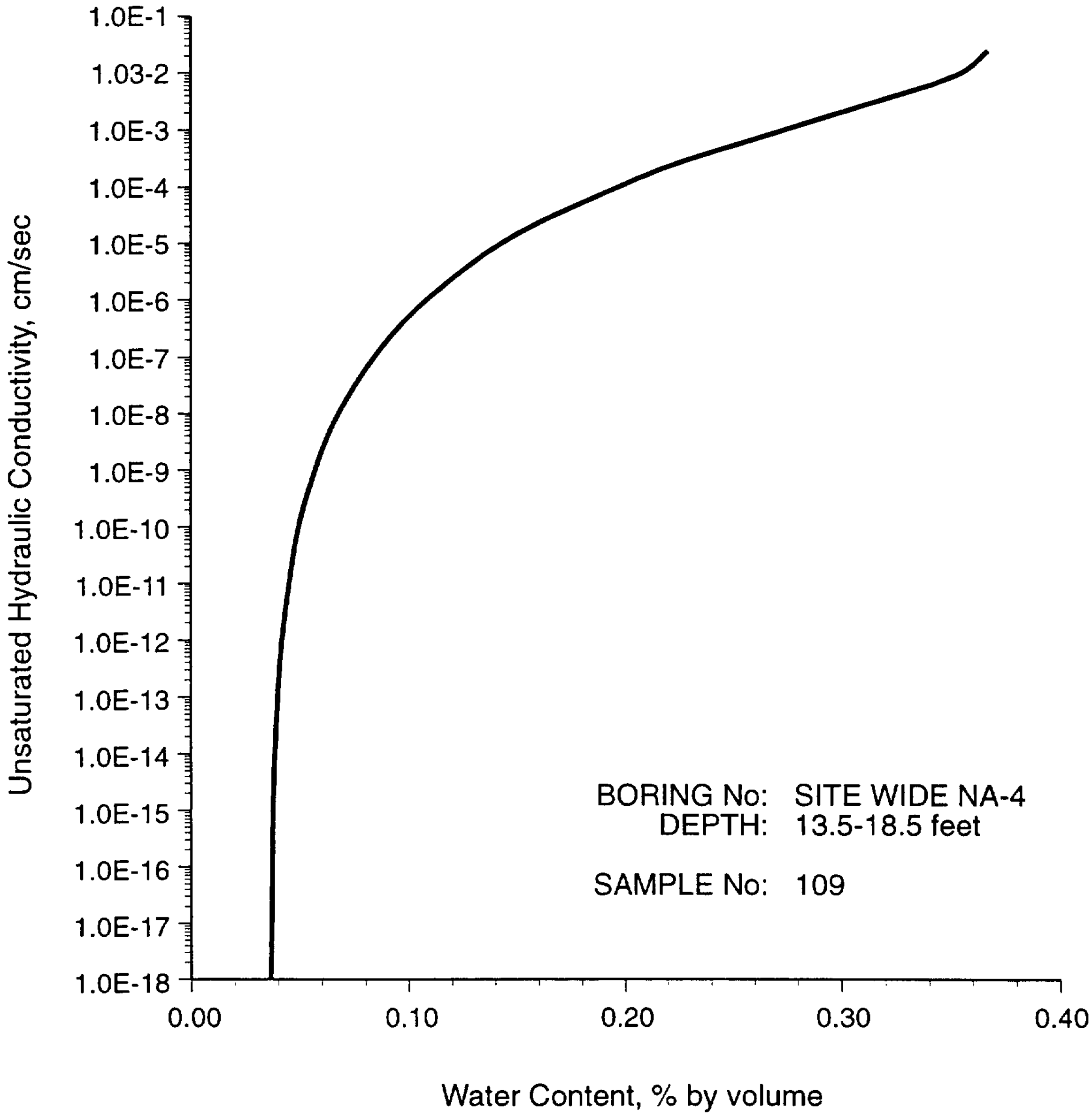


Figure 4.1.2-2. Example of Changes in Unsaturated Hydraulic Conductivity With Varying Water Content

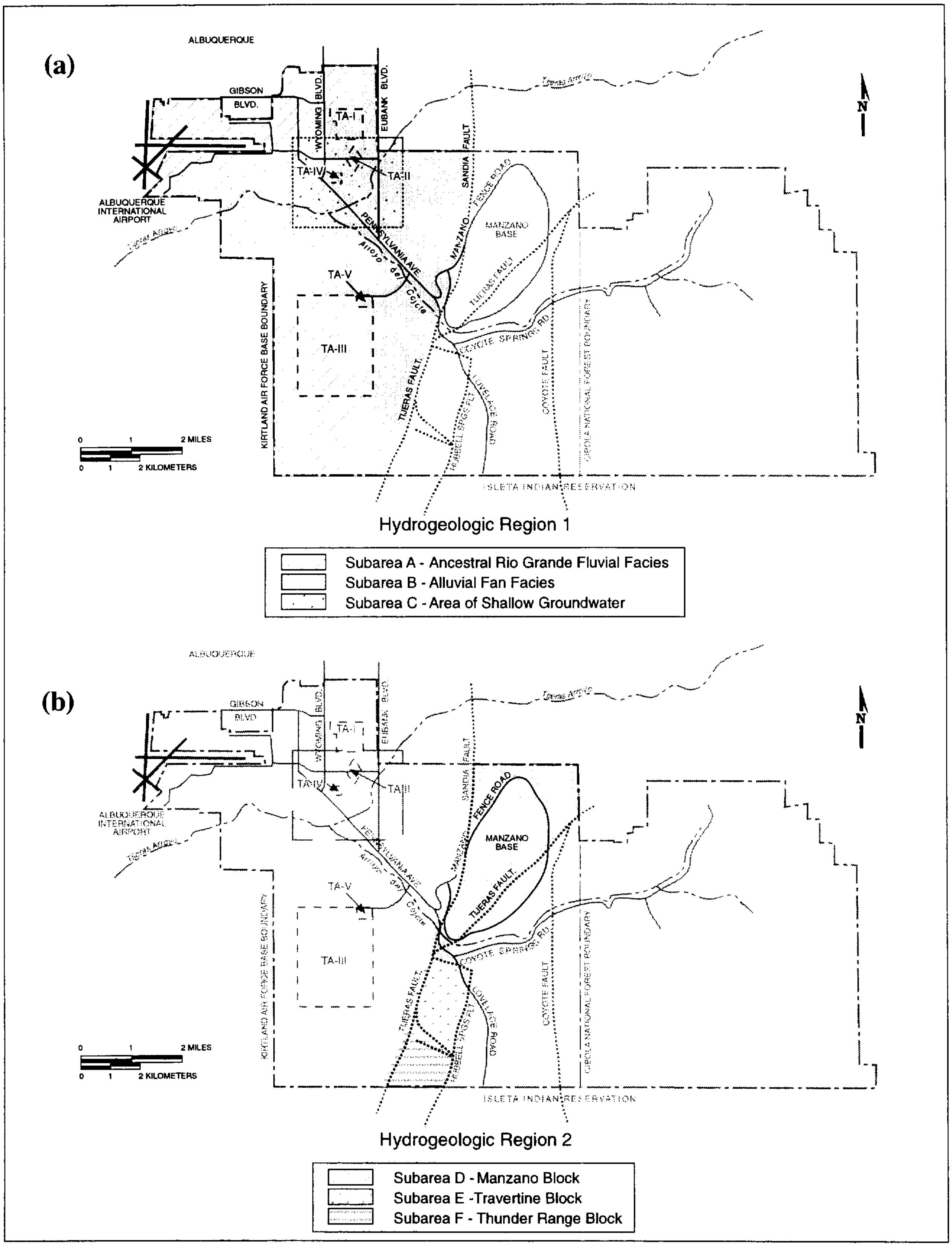


Figure 4.2.2-1. Hydrogeologic Regions and Subareas in the Conceptual Model (page 1 of 2)

(c)

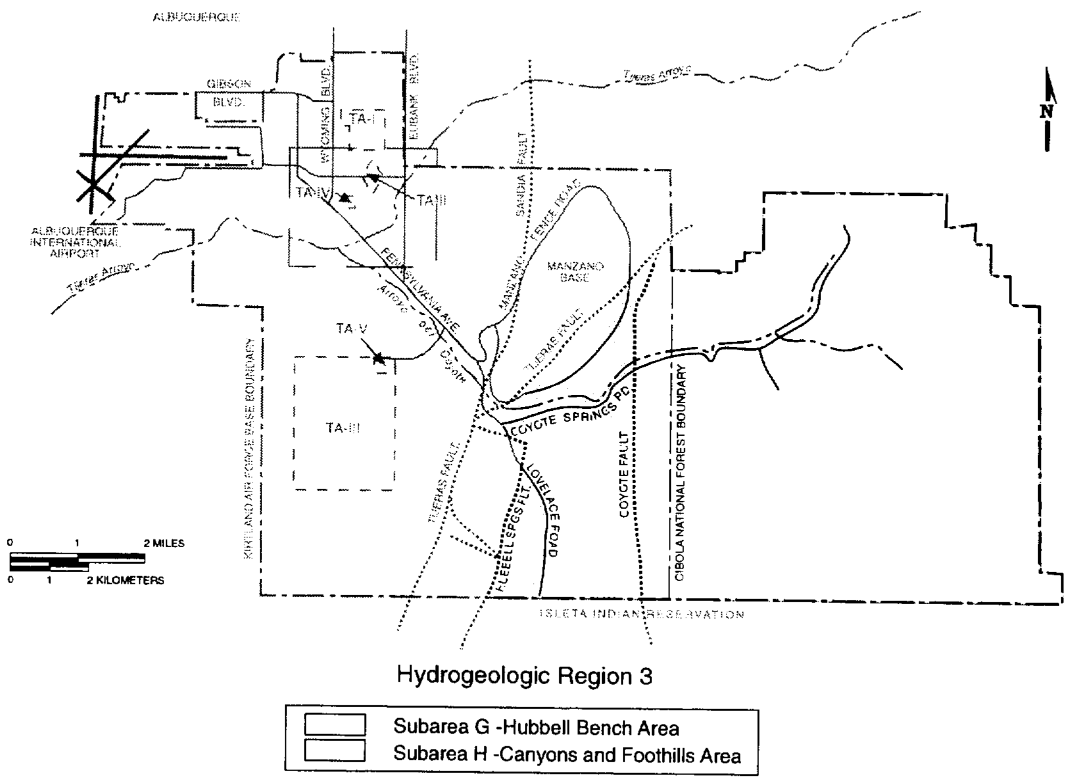


Figure 4.2.2-1. Hydrogeologic Regions and Subareas in the Conceptual Model (page 2 of 2)

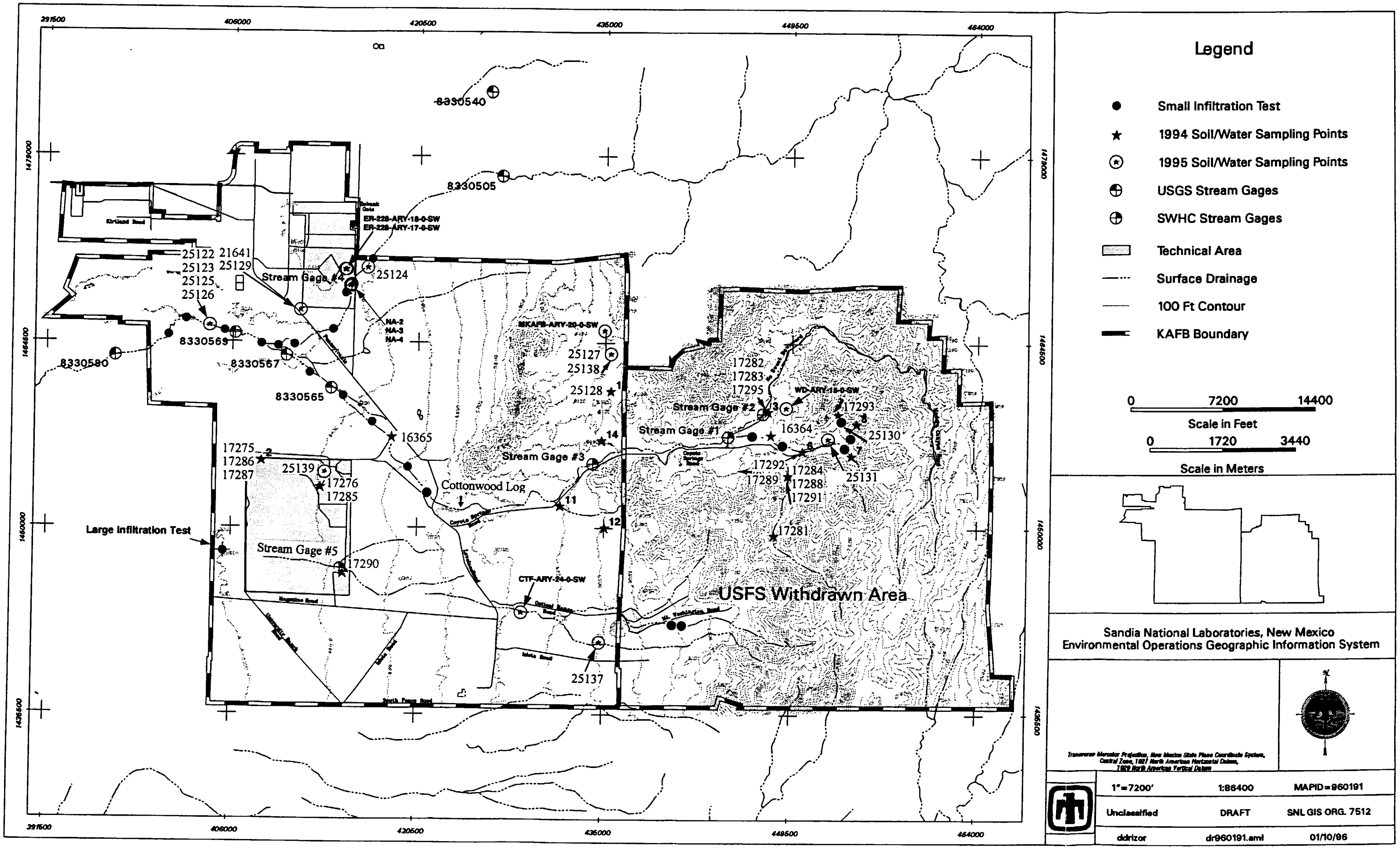


Figure A-1. FY-1995 Work - Neutron Access Tubes in Arroyos, Water Quality Samples, Streamflow Gages, Small-Scale Infiltration Tests, the Combined Aquifer/Infiltration (Large-Scale) Test, and the Flood-Deposited Log

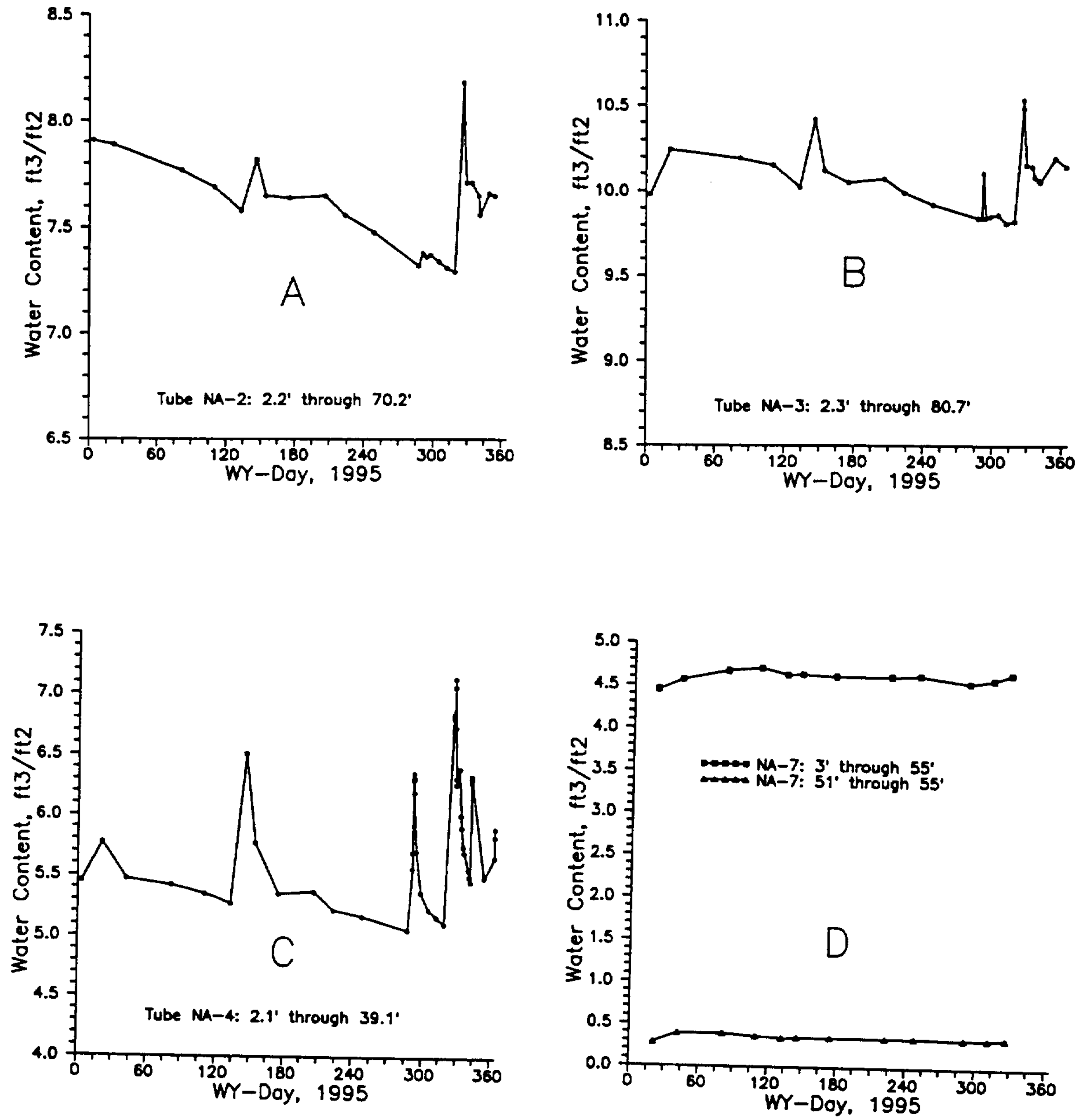


Figure A-2. Cumulative Soil Water Contents Over Time at Neutron Access Tube Sites in Tijeras Arroyo. Tubes NA-2 (A) and NA-3 (B) have fine materials at approximately 5 to 9 ft below the surface. Tube NA-4 (C) has no fine layer, causing it to respond more than the others Tube NA-7 (D) is about 25 ft away from the channel, and shows response only in the top few feet due to rainfall, and a slight, much delayed response at 50 ft to 55 ft due to streamflow.

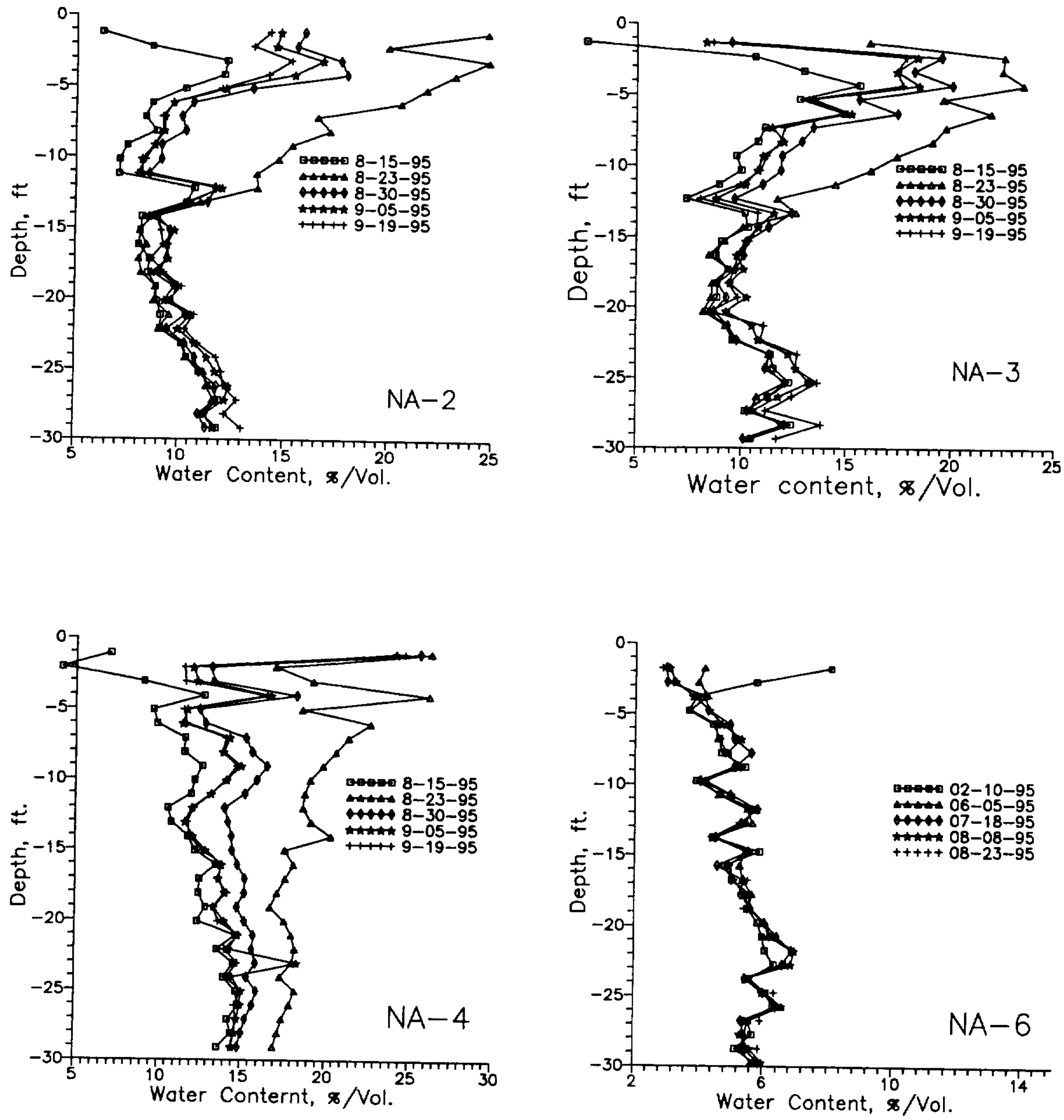


Figure A-3. Water Contents With Depth on Selected Dates for Four Neutron Tubes in Tijeras Arroyo. Tubes NA-2 and NA-3 have a fine textured layer between about 5 and 10 ft depth, Tube NA-4 has no fine layer, and Tube NA-6 is about 50 ft outside the main channel.

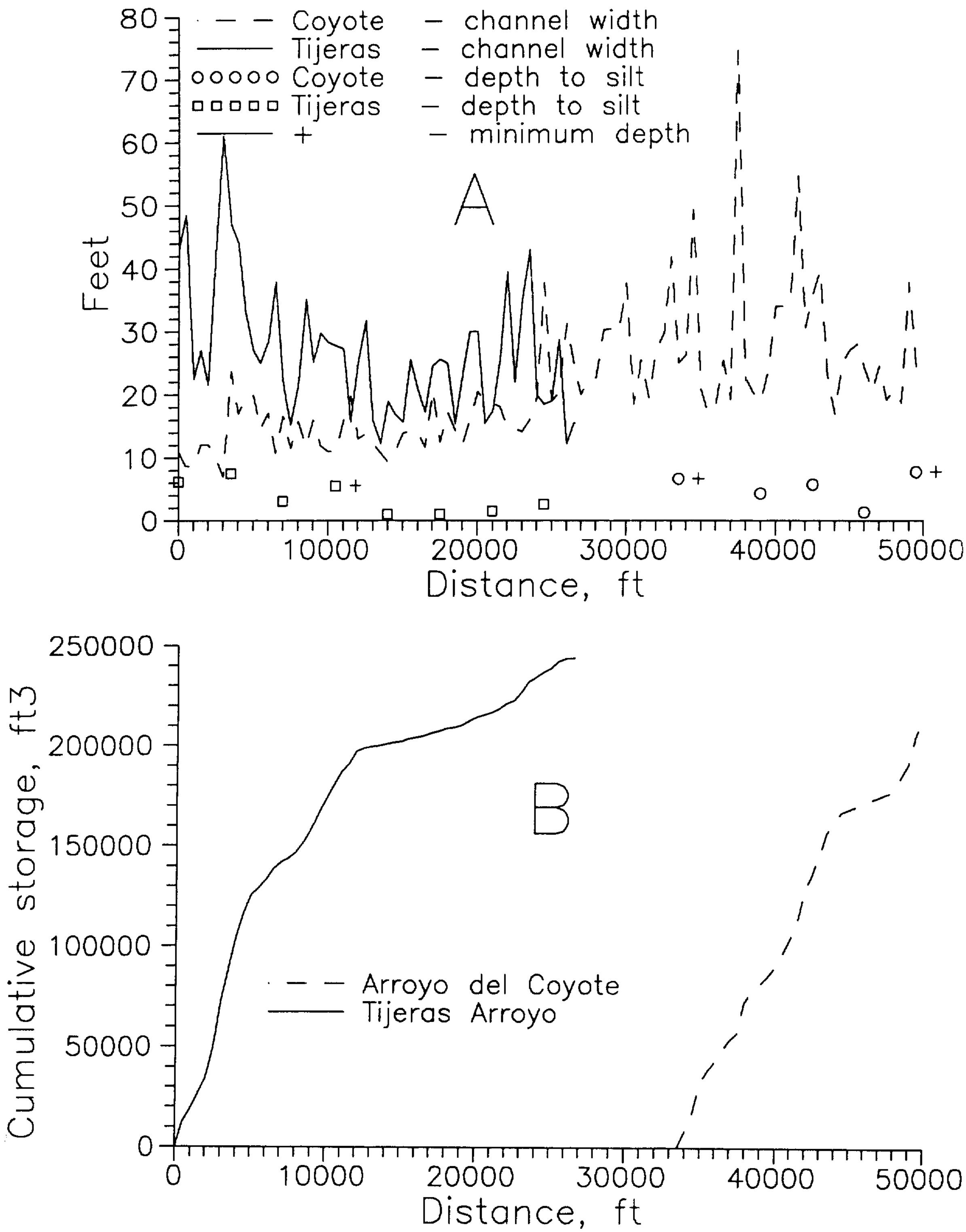
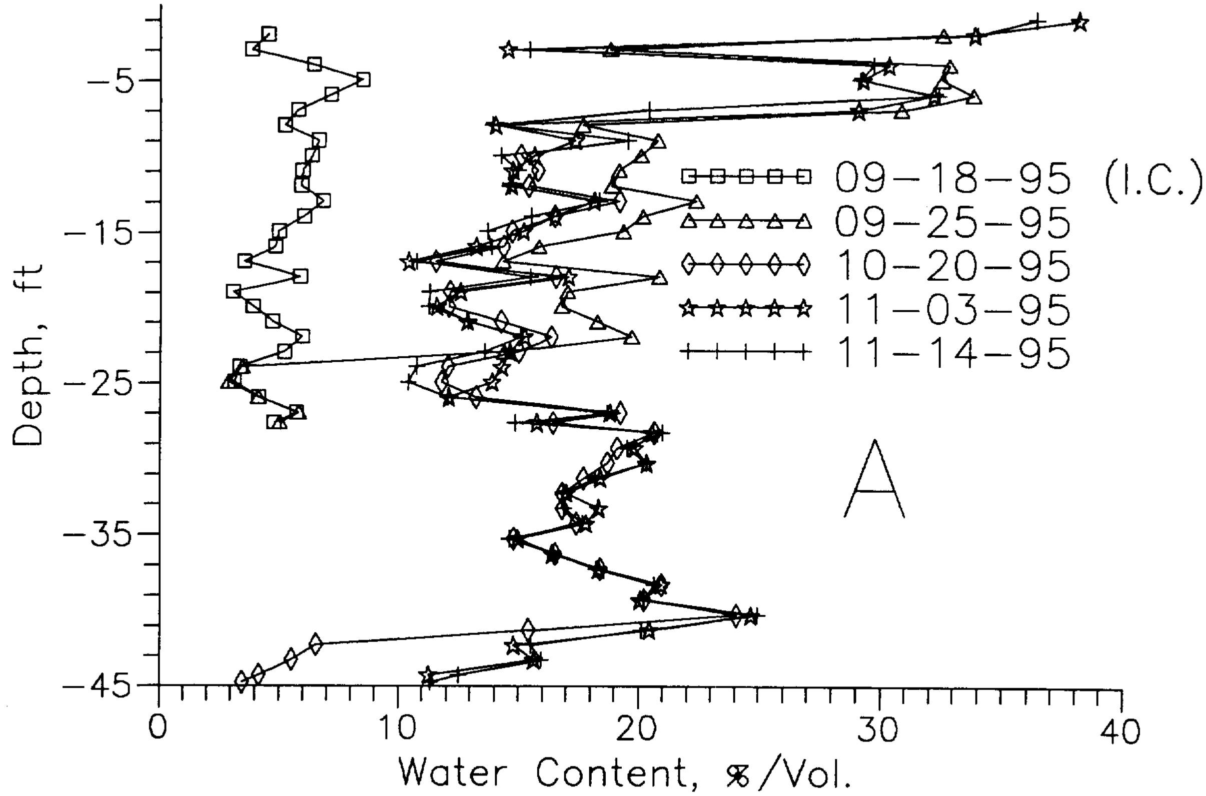


Figure A-4. Characteristic Channels and Near-Surface Materials in Tijeras Arroyo and Arroyo del Coyote. (A) Bankfull channel width and depth to first fine textured layer. (B) Cumulative available storage, assuming a 10% by volume increase in water content above the fine textured layer. Distance is measured from north KAFB boundary fence on Tijeras Arroyo, and from No-Sweat Boulevard on Arroyo del Coyote. No estimates of silt layer depth or potential storage were made upstream of Lovelace Road on Arroyo del Coyote.



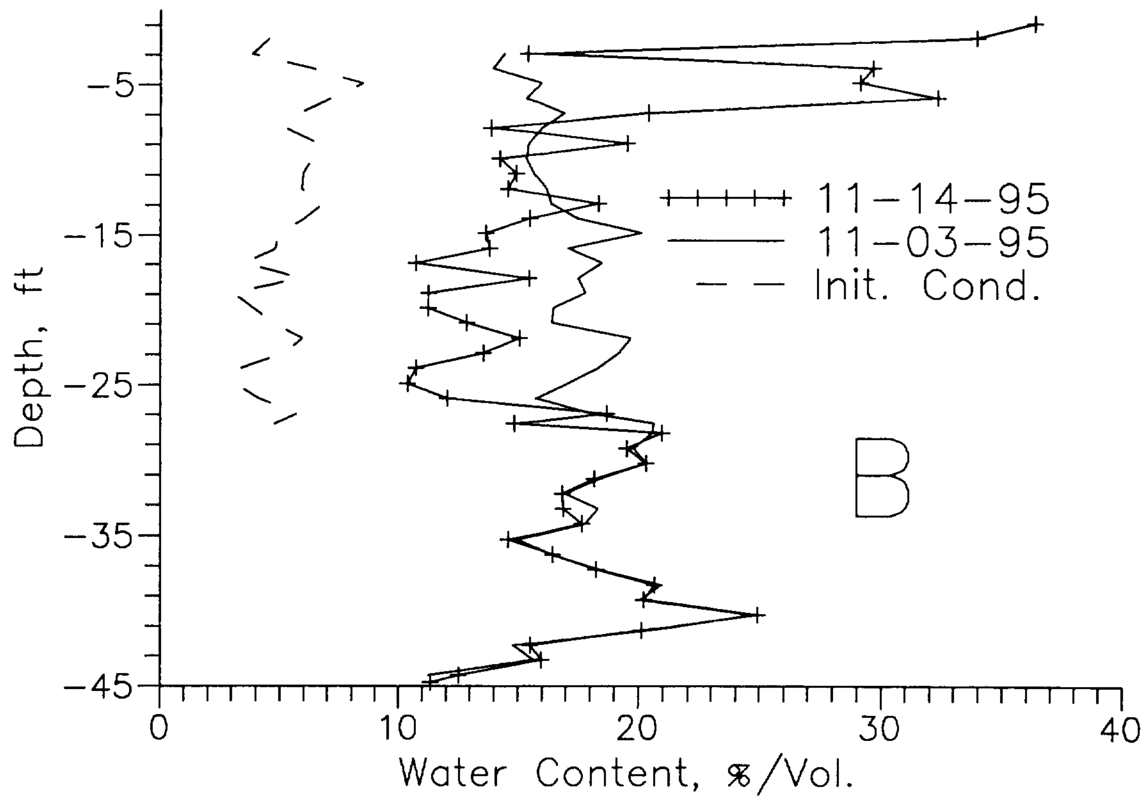


Figure A-5. Water Contents Over Time Beneath Pond at MRN-1 Aquifer/Infiltration Test Site. (A) Combined data from 3 tubes, the upper 10 ft showing effects of bentonite. (B) Data from single, 45-ft deep tube with no bentonite on November 3 compared to combined tube data (with 10 ft bentonite seal) collected November 14. The upper 35 ft of the 45-ft tube were installed through a 6-in. borehole, while other holes were hand-augered to about a 3.25-in. diameter.

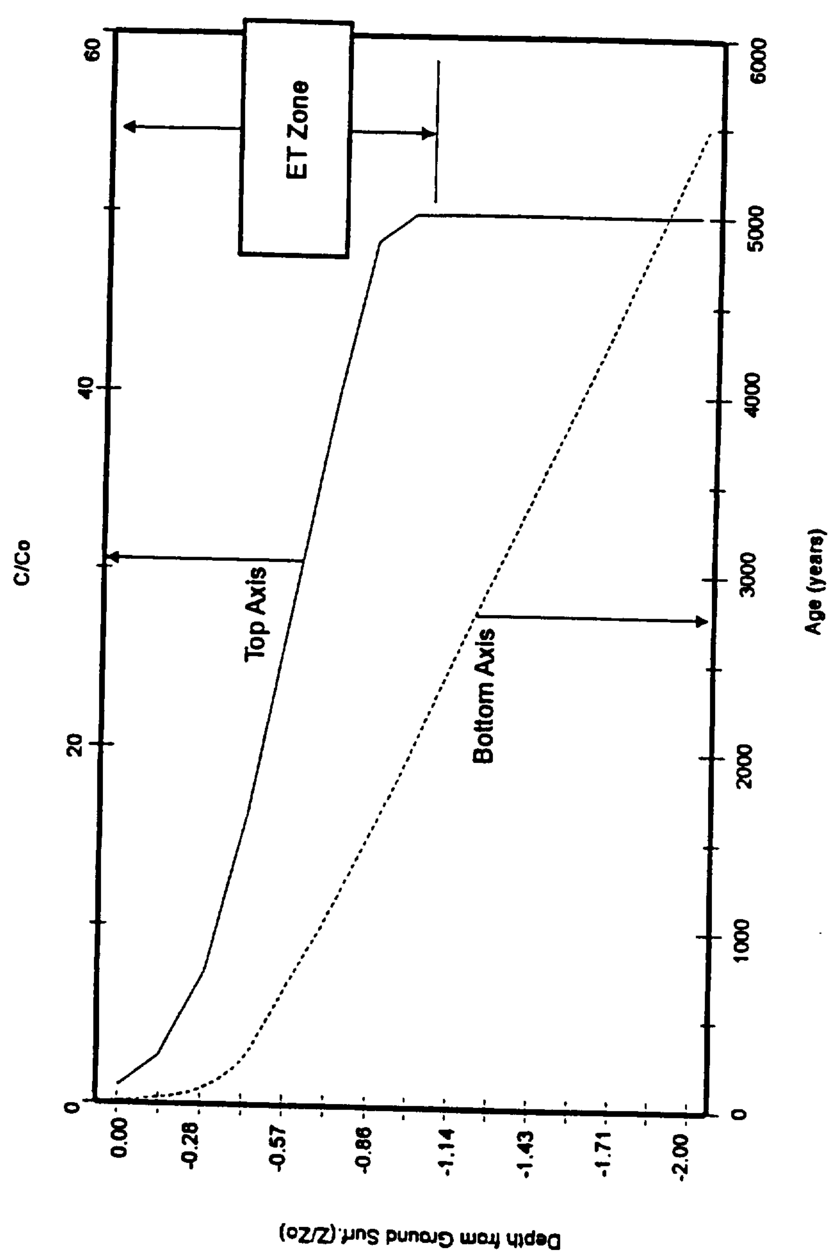


Figure B-1. Chloride Concentrations Approaching Constant Value

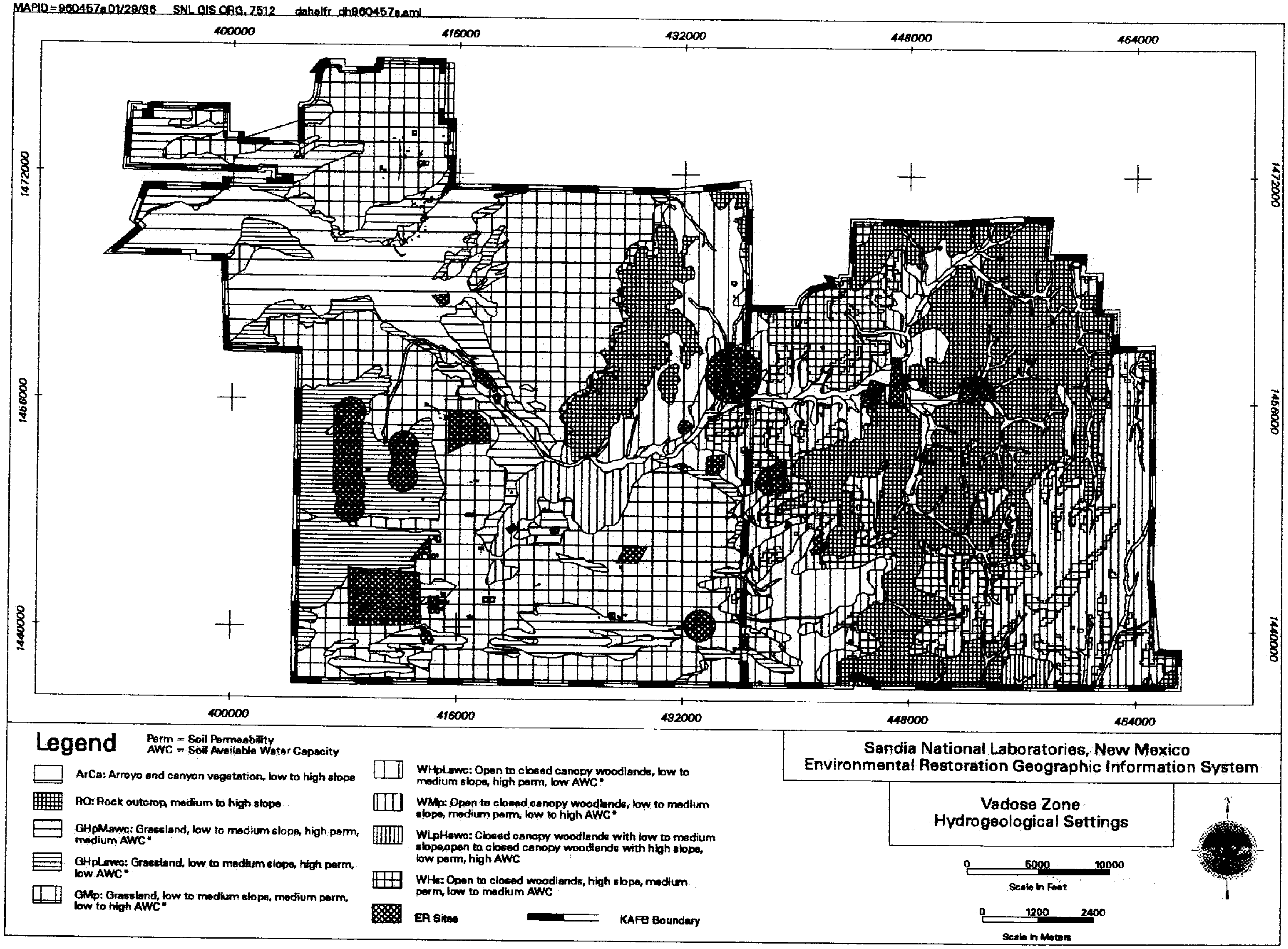


Figure B-2. Map of Areal Coverage of Each Vadose Hydrogeologic Zone Setting

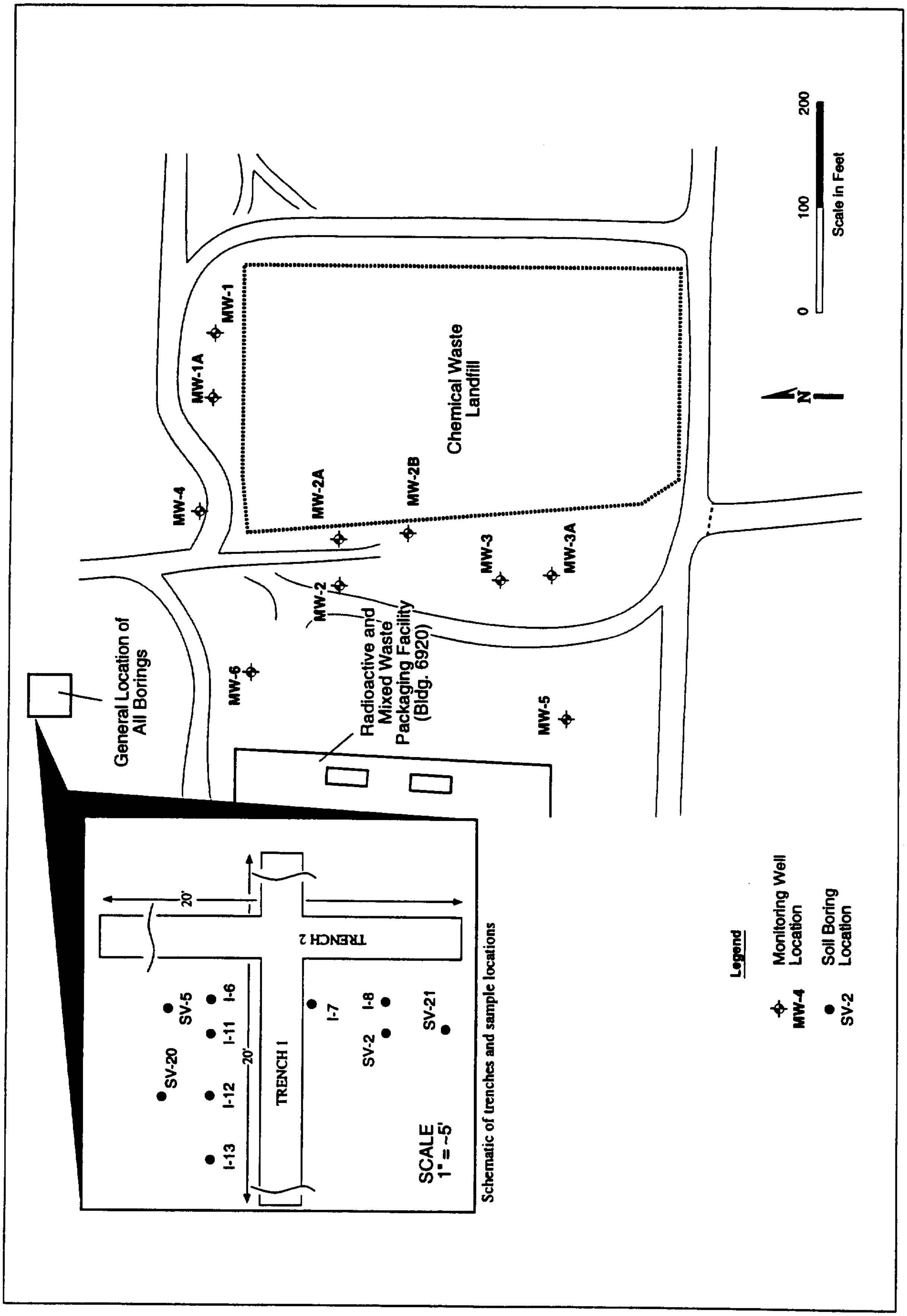


Figure B-3. Chemical Waste Landfill Recharge Study Site

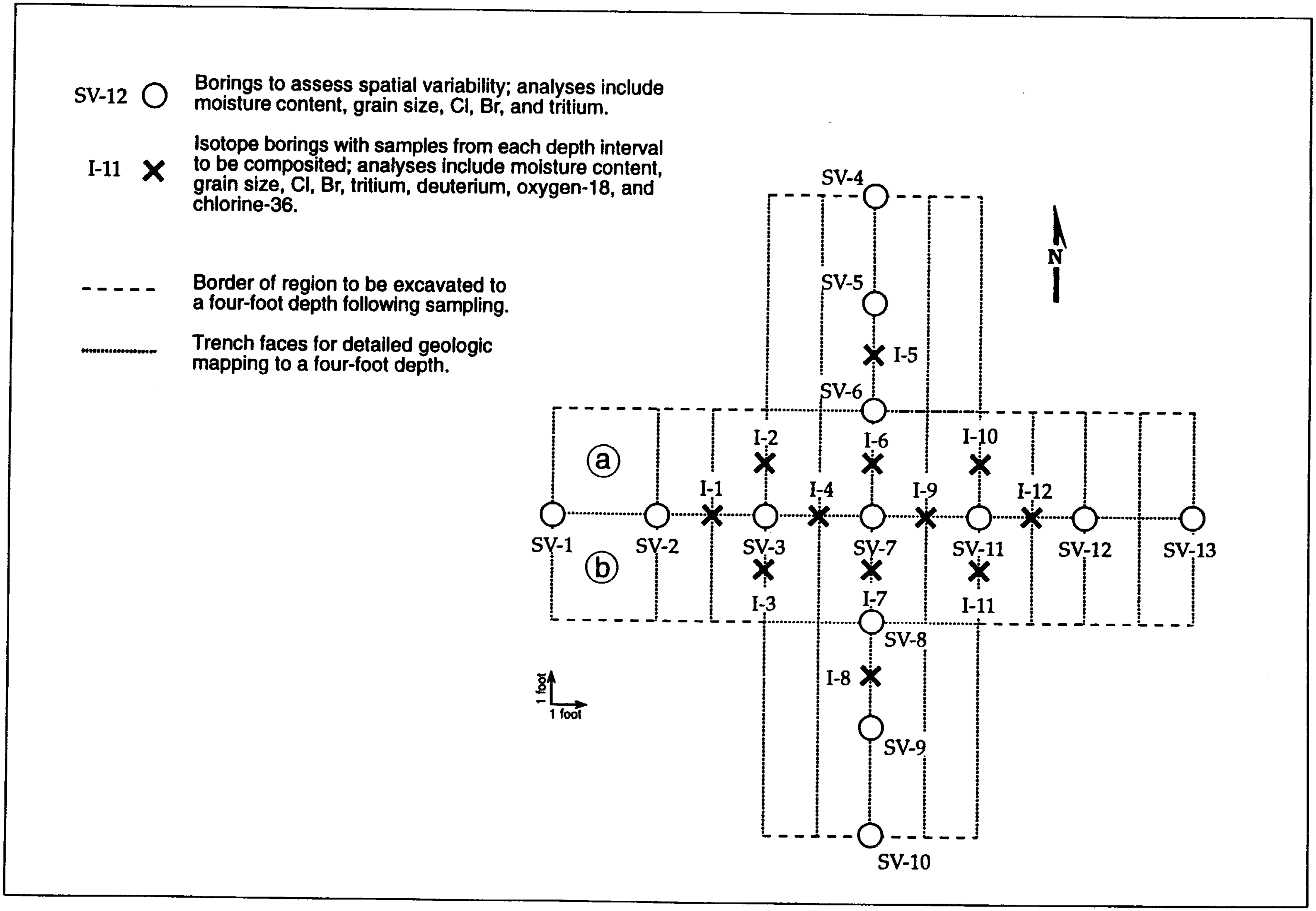


Figure B-4. Grid Layout for Sampling Locations and Postsampling Excavation Boundaries and Transects

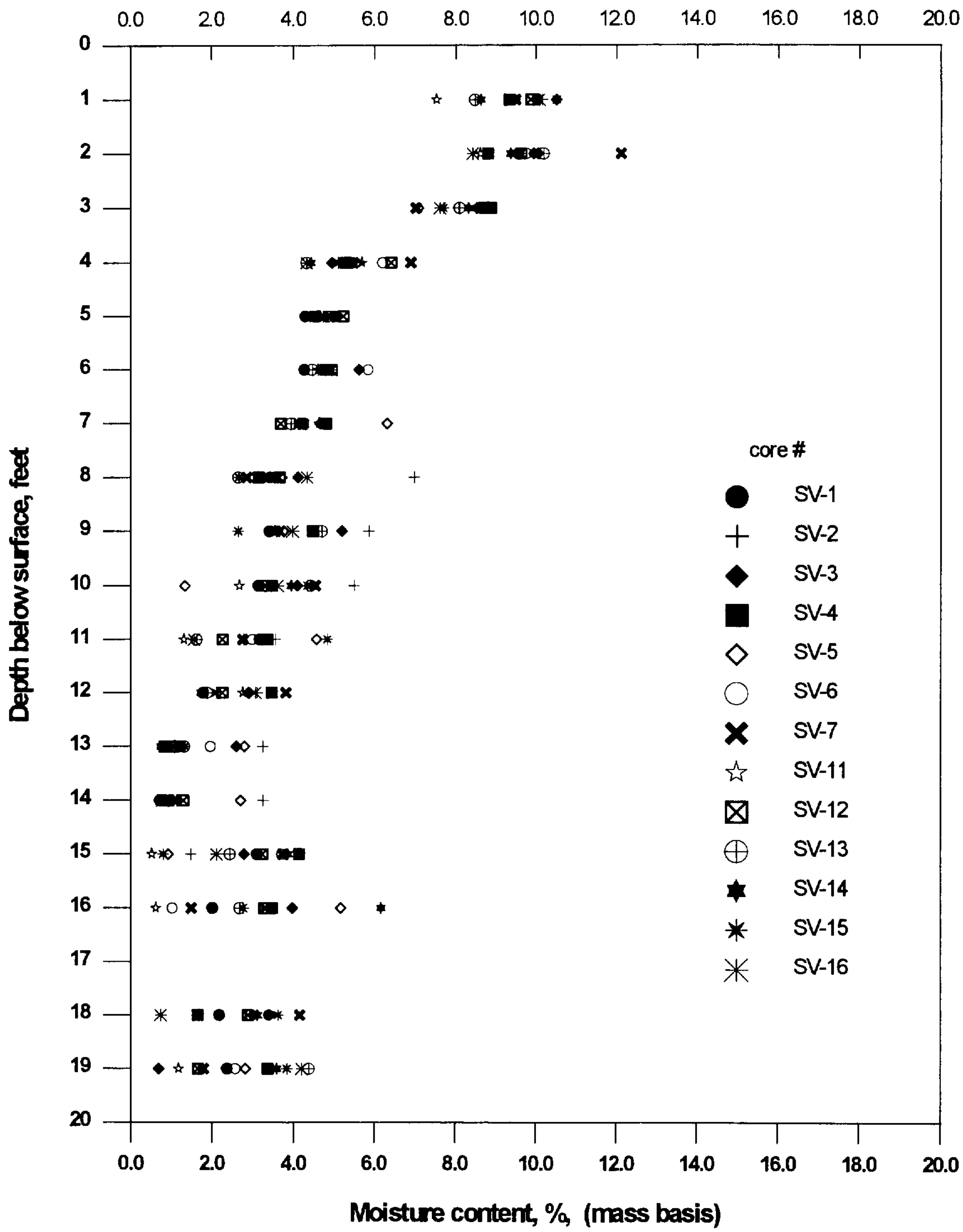


Figure B-5. Chemical Waste Landfill Recharge Phase II Moisture Content Variability

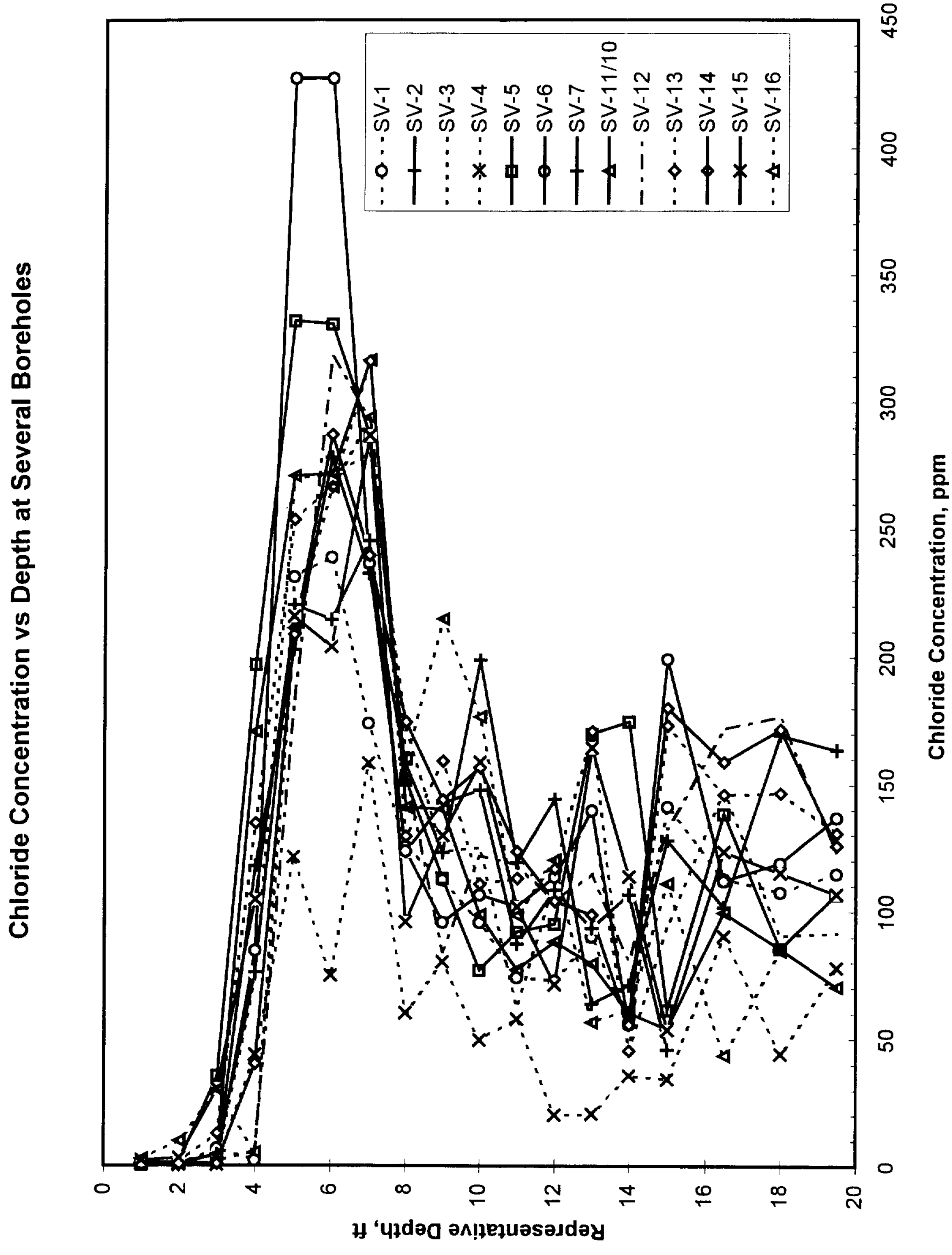


Figure B-6. Depth Versus Chloride

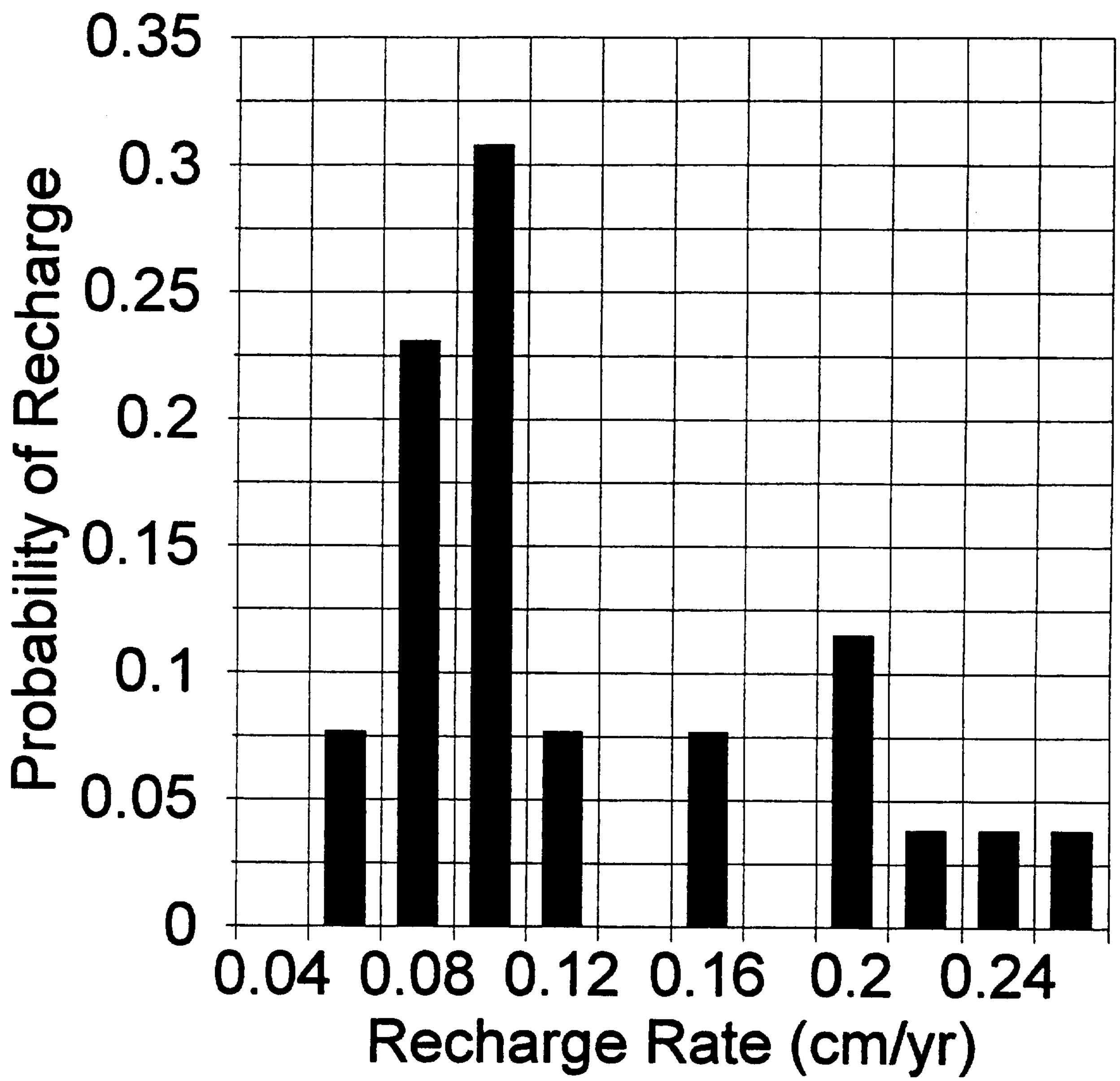


Figure B-7. Histogram of Recharge Estimates

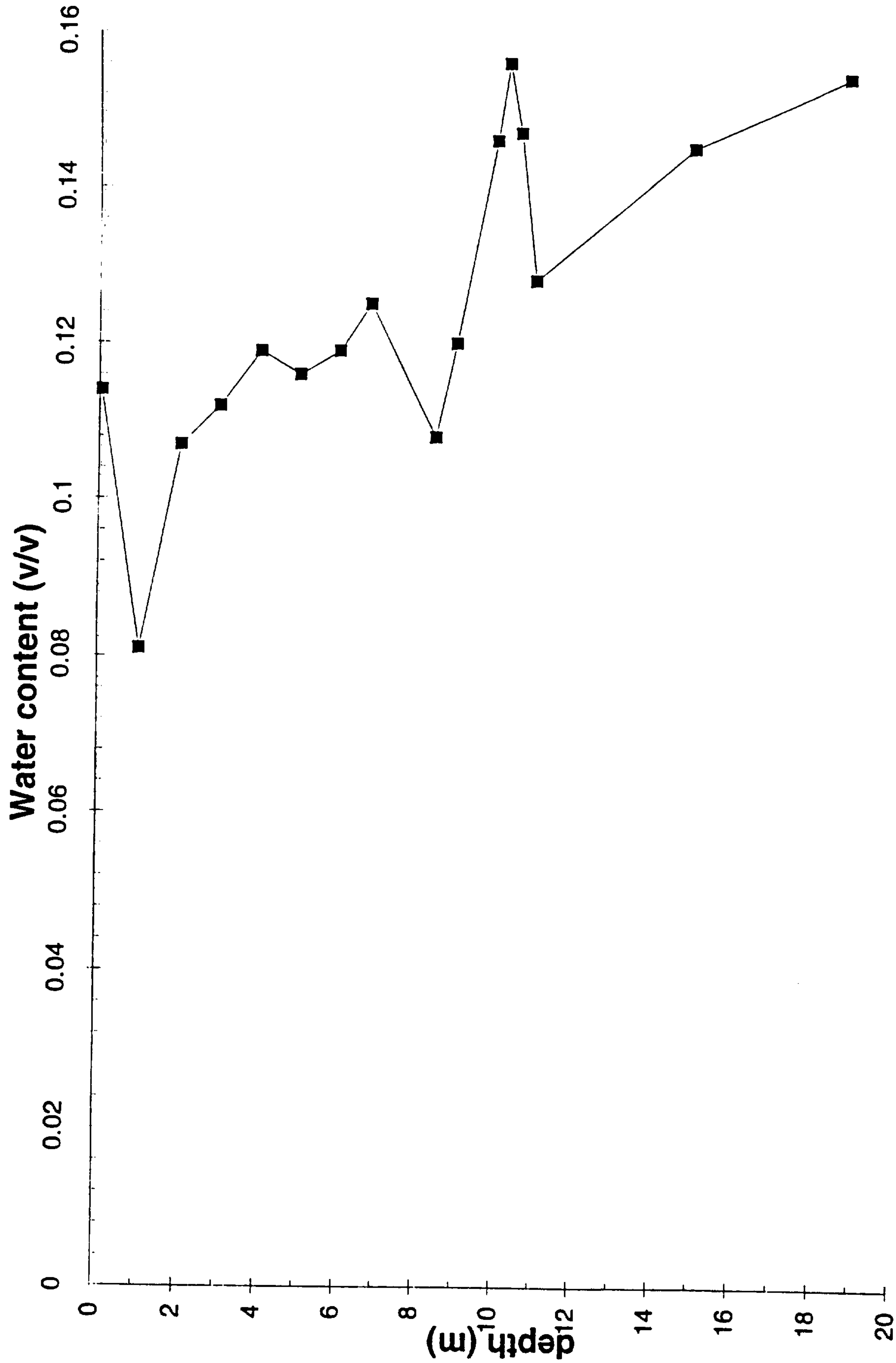


Figure B-8. Moisture Content Versus Depth (SFR 1-D)

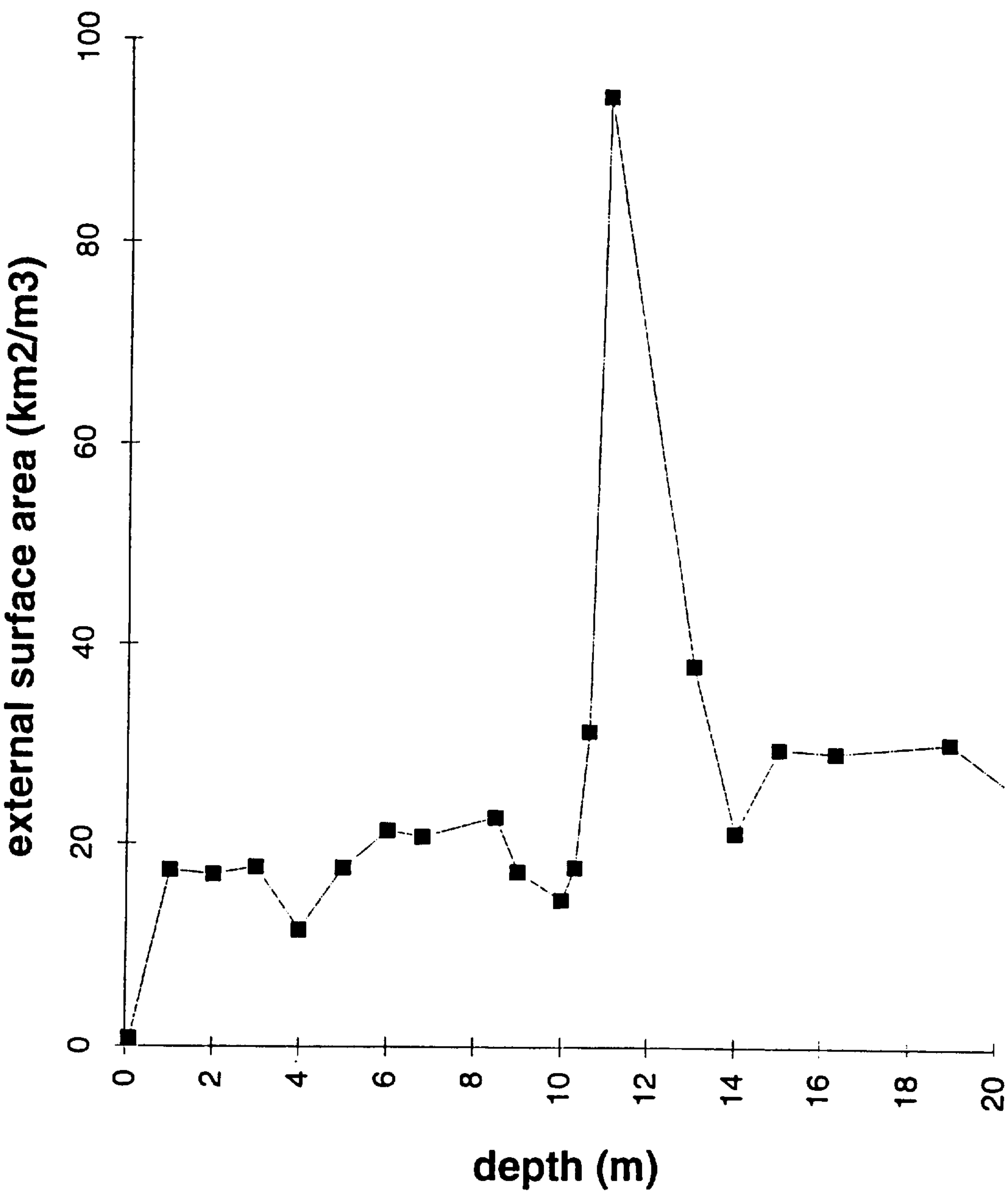


Figure B-9. Volumetric External Surface Area Results Versus Depth

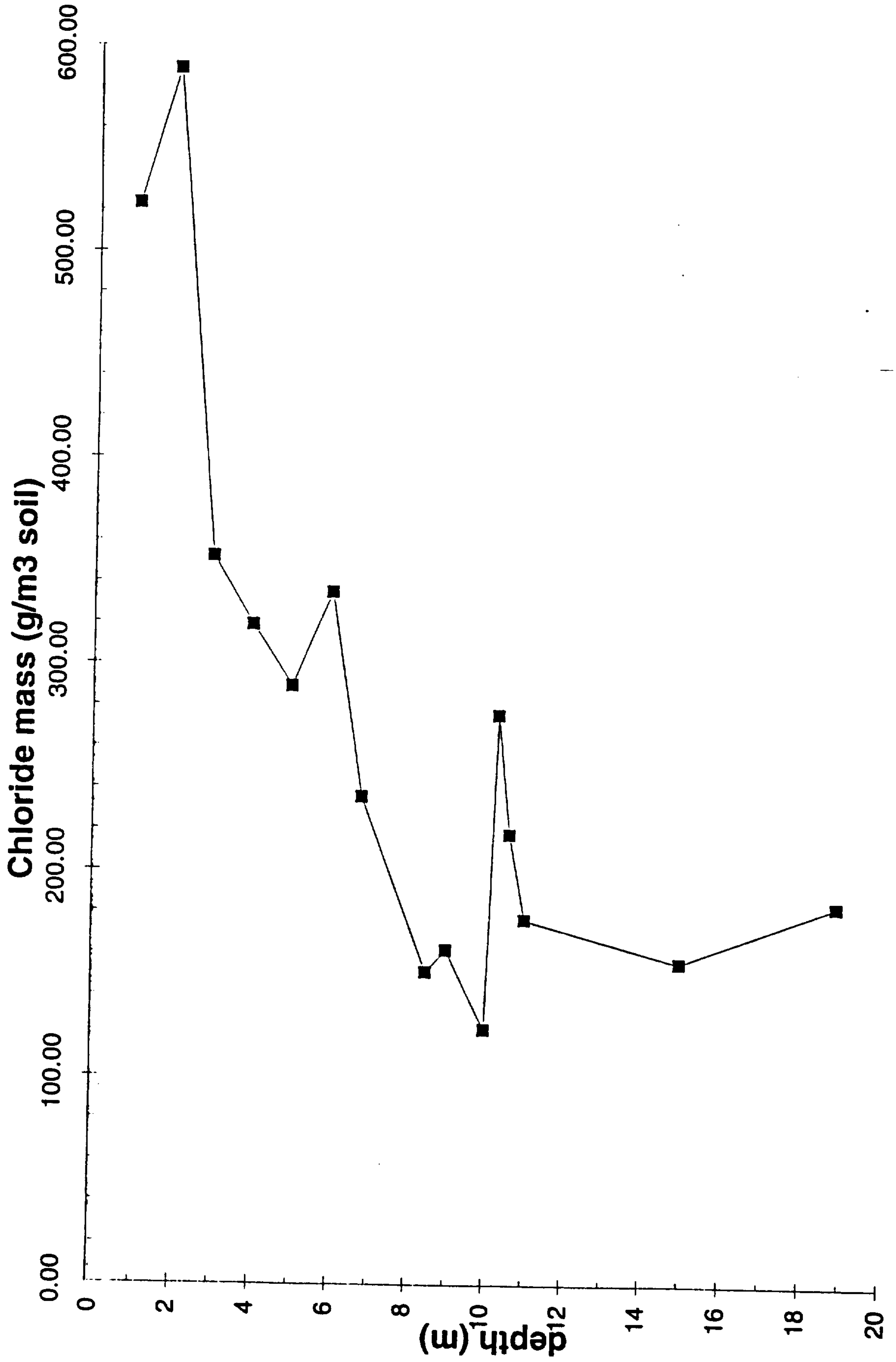


Figure B-10. Depth Profile of Chloride

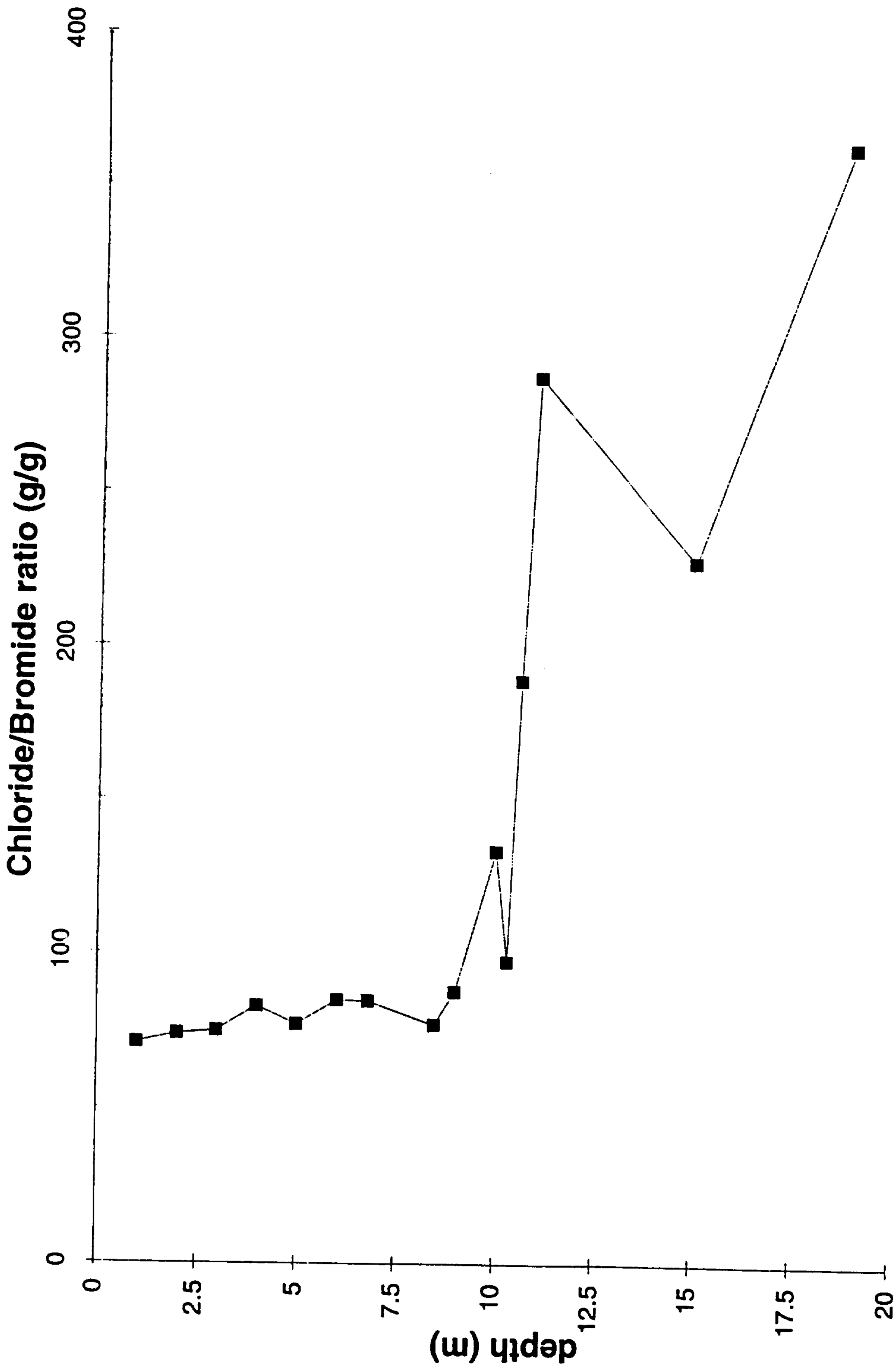


Figure B-11. Depth Profile of Chloride to Bromide Ratio

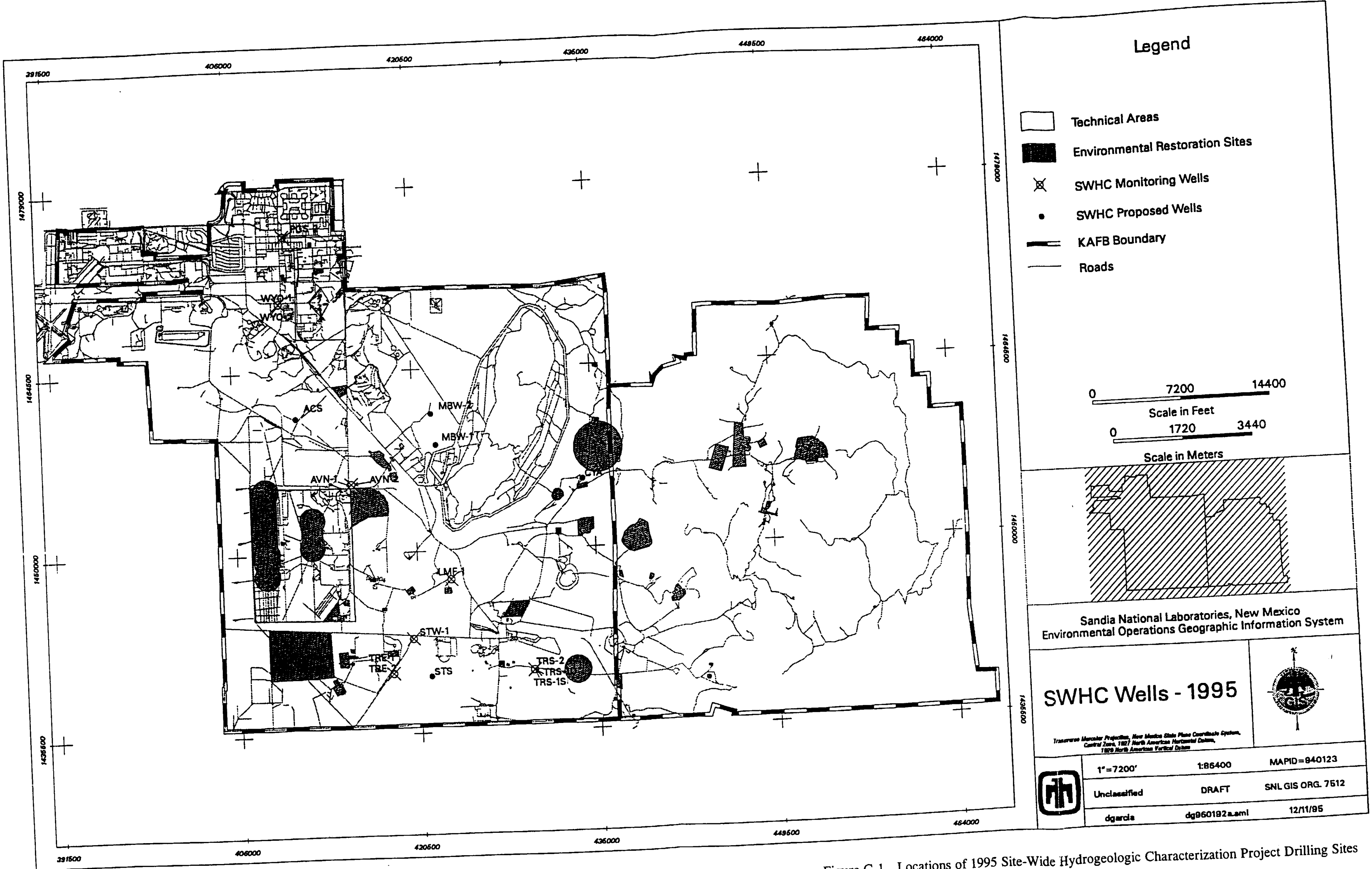


Figure C-1. Locations of 1995 Site-Wide Hydrogeologic Characterization Project Drilling Sites

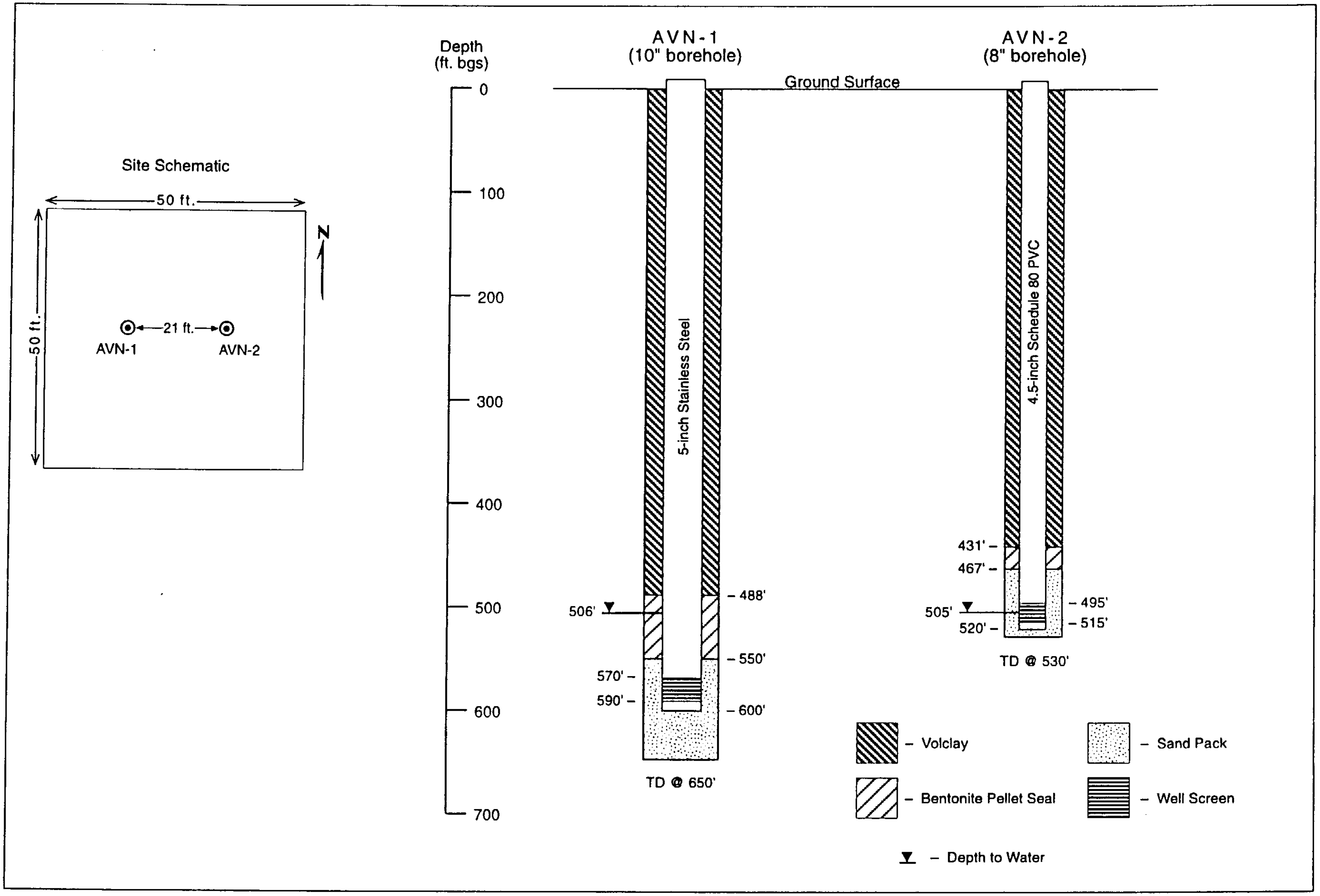


Figure C-2. Well Completion Schematic for Area V North Drill Site

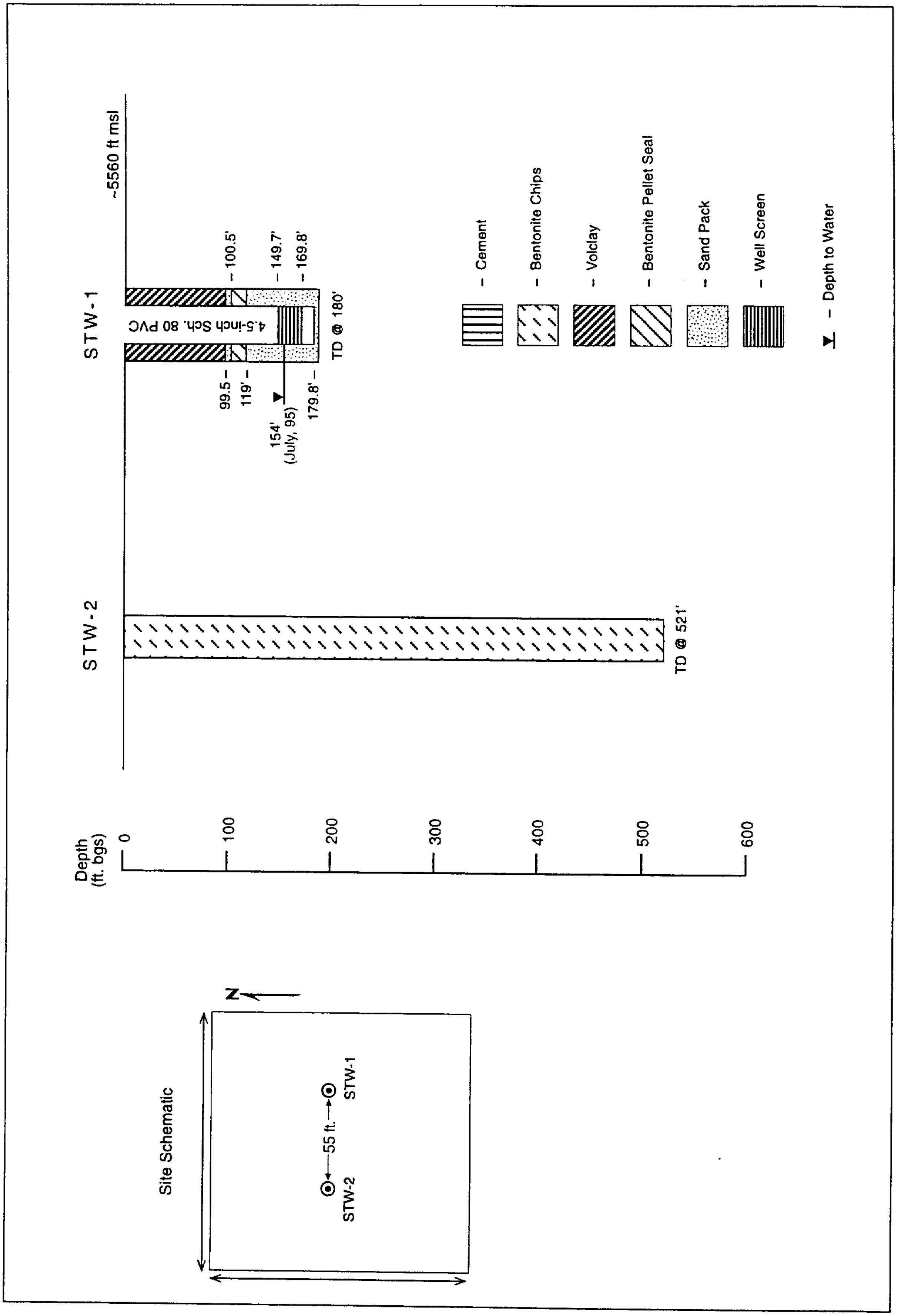


Figure C-3. Well Completion Schematic for Solar Tower West Drill Site

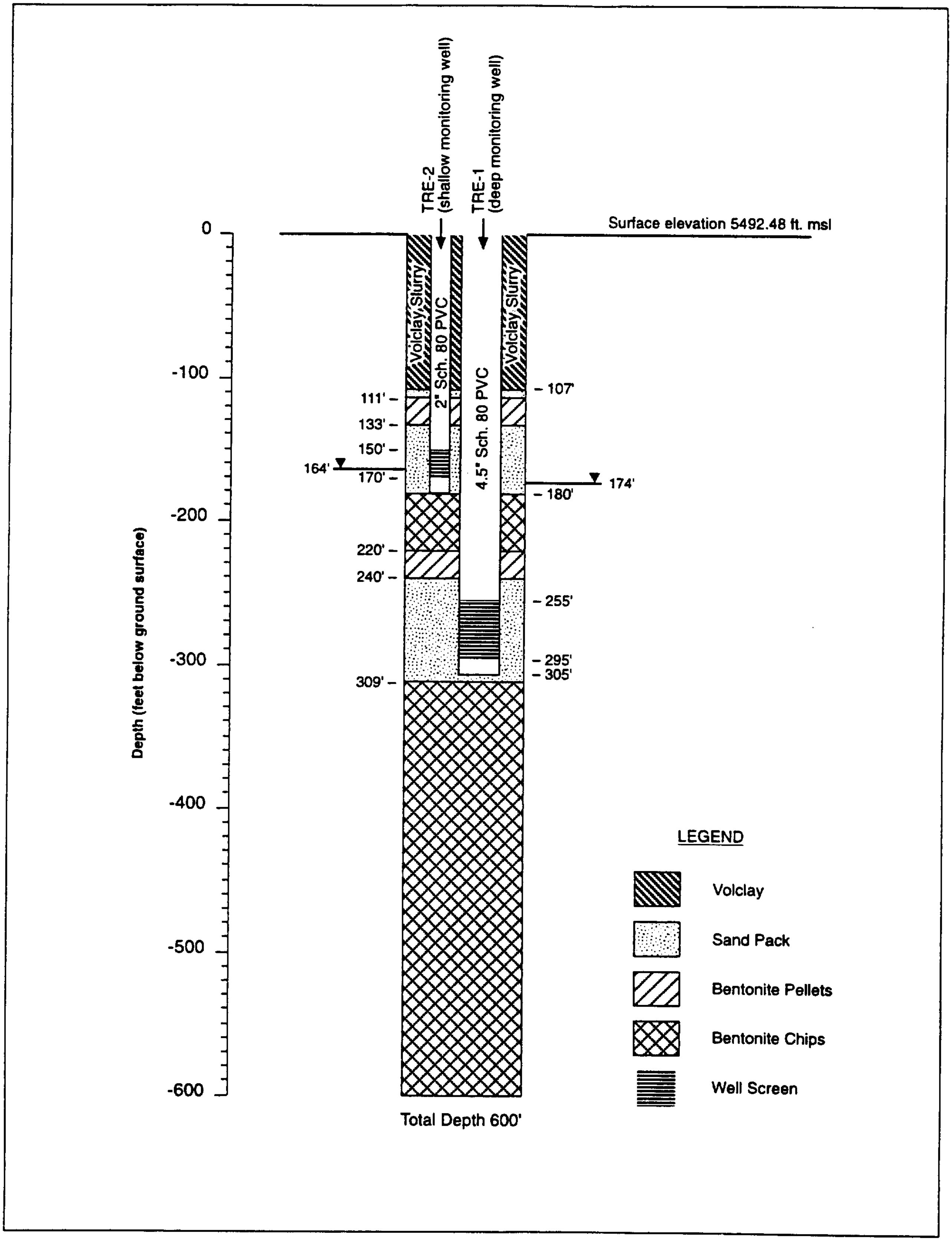


Figure C-4. Well Completion Schematic for Thunder Range East Drill Site

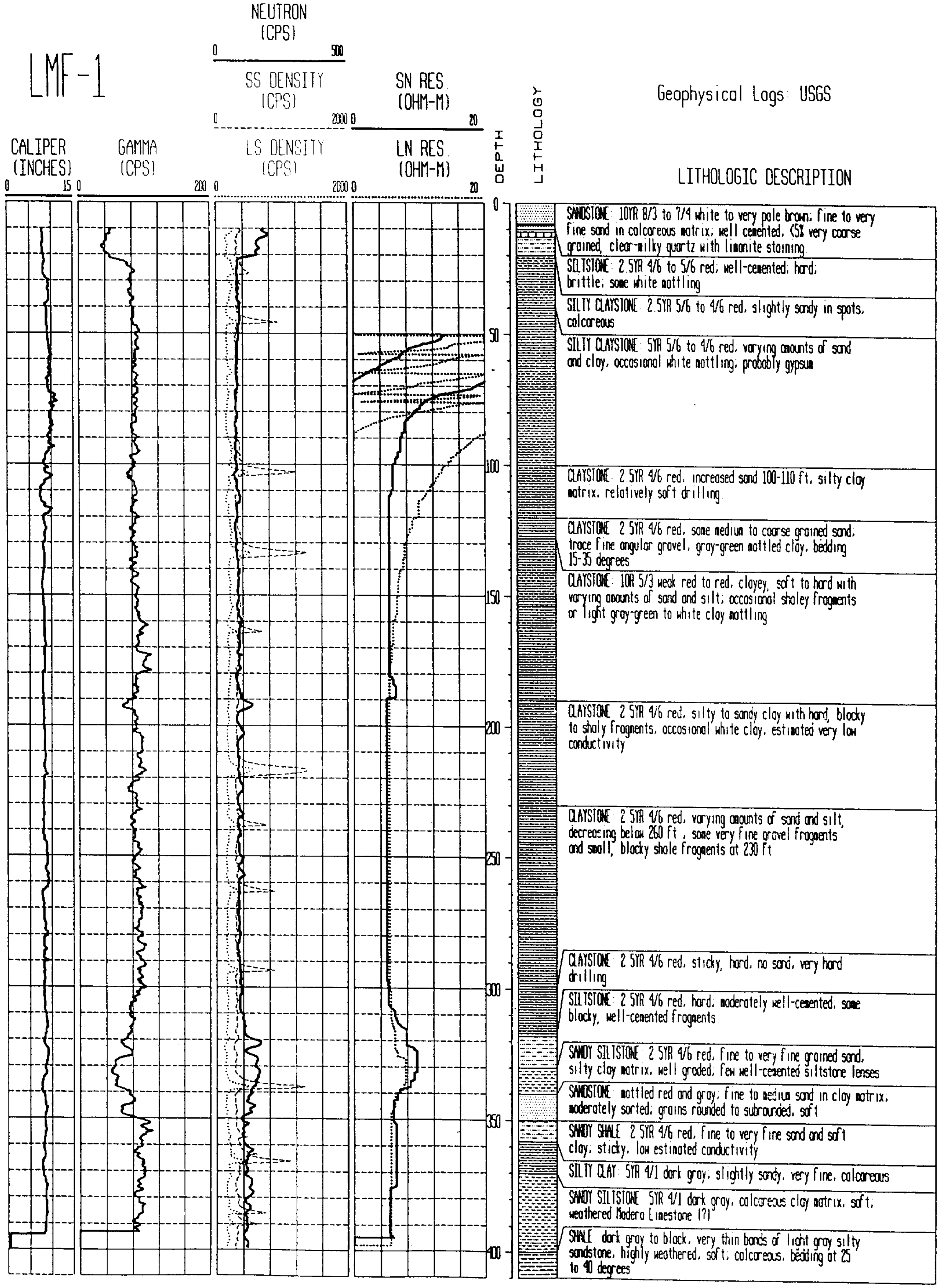


Figure C-5. Lithologic and Geophysical Logs of LMF-1

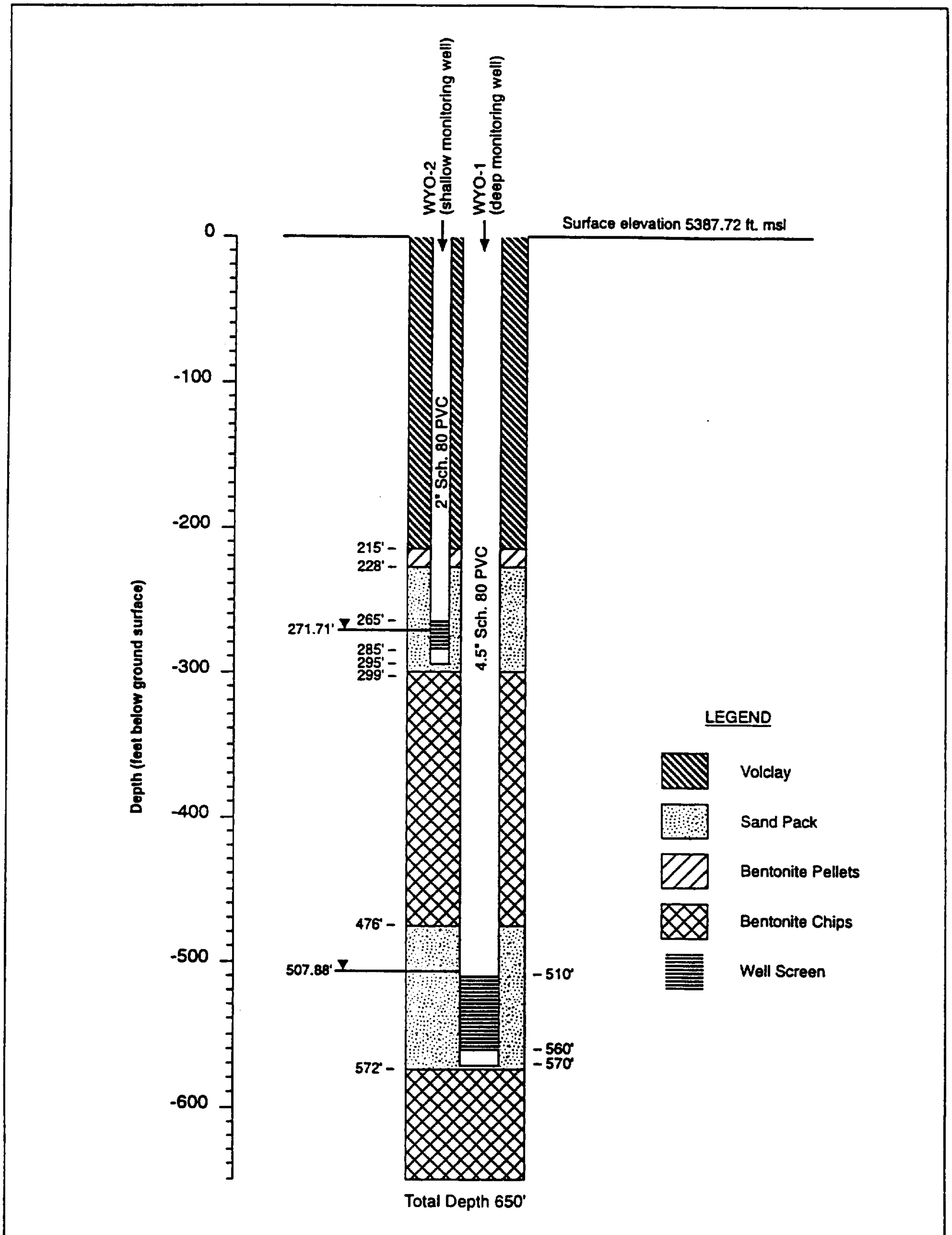


Figure C-6. Well Completion Schematic for Wyoming and Ordnance Road Drill Site

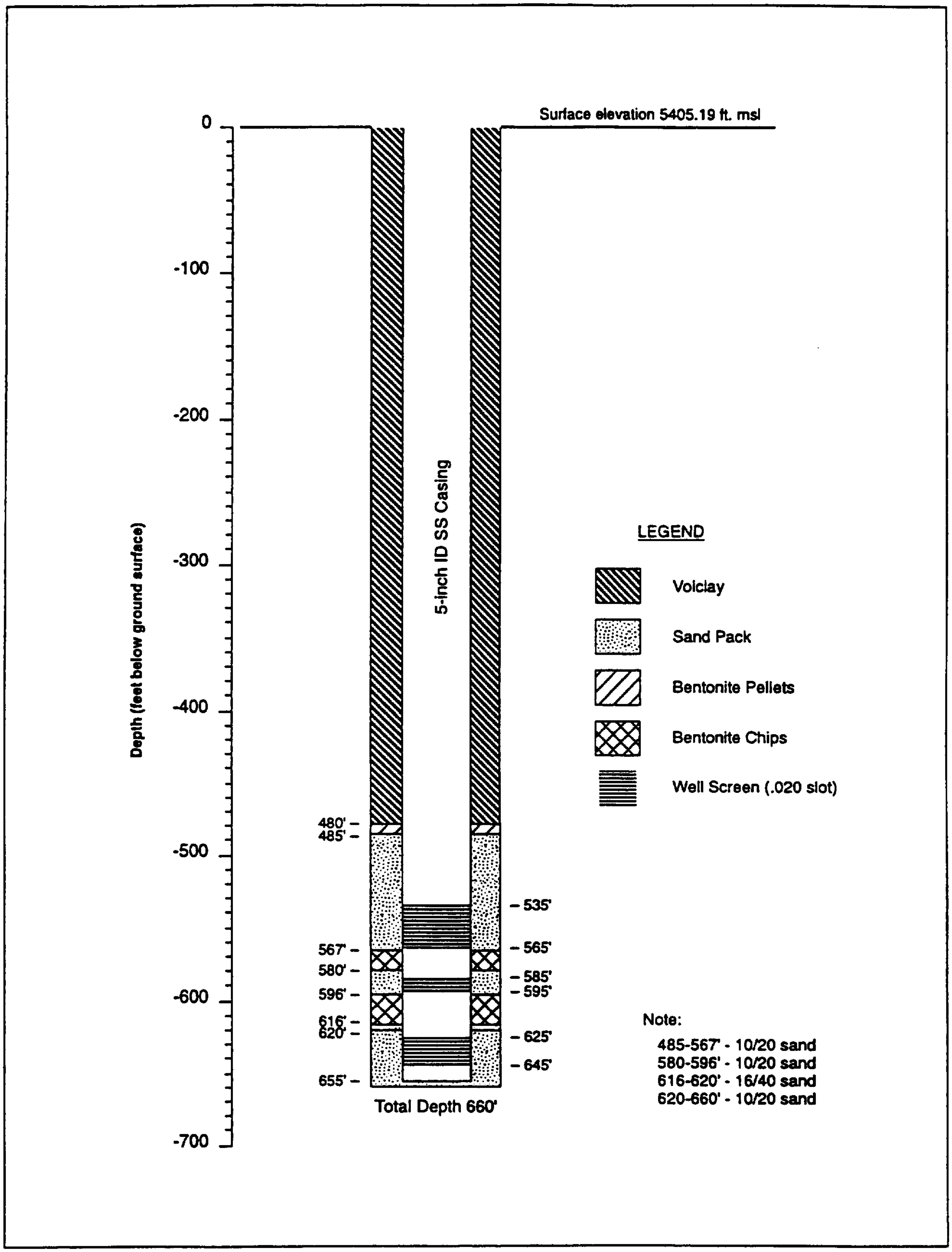


Figure C-7. Well Completion Schematic for Parade Ground South Drill Site

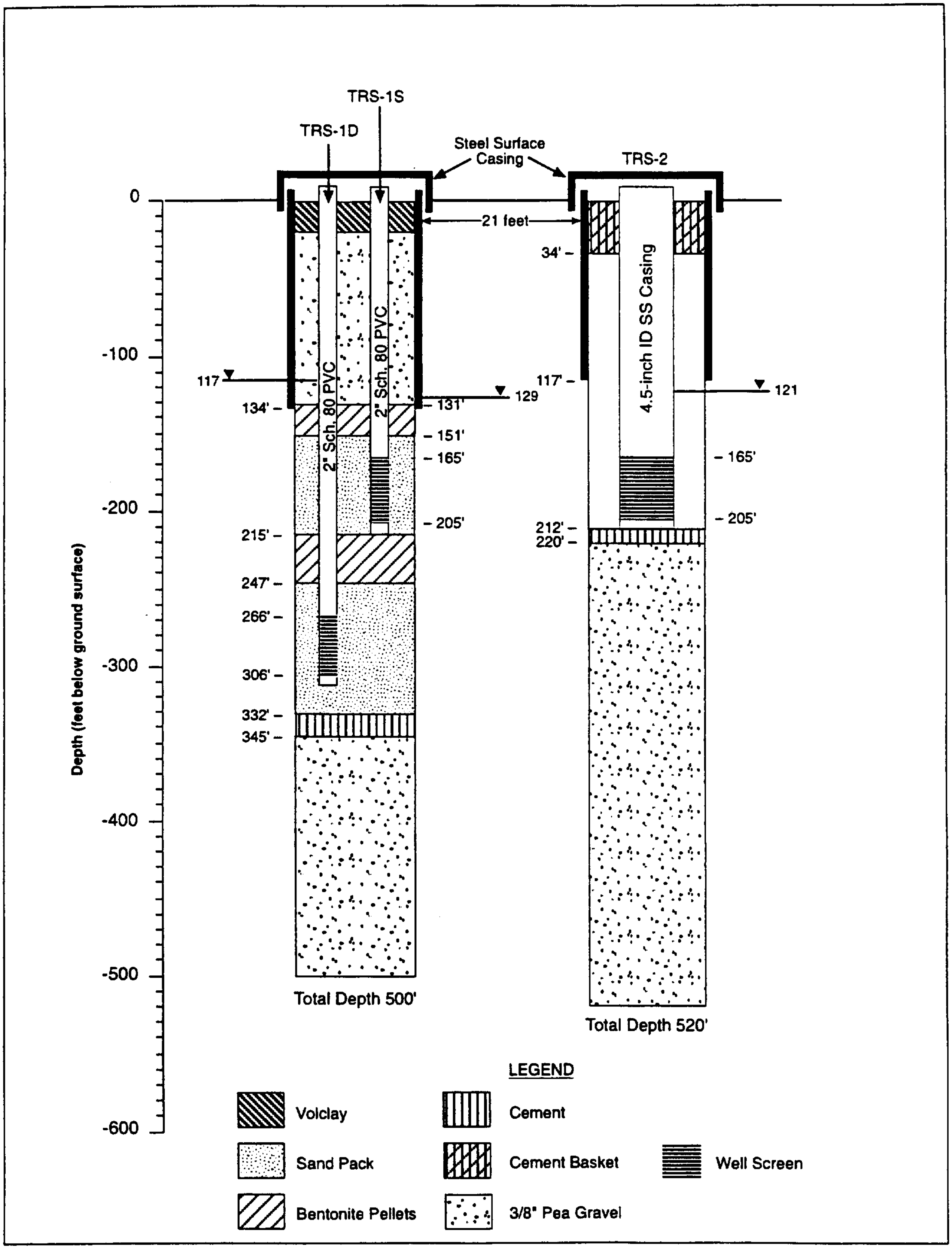


Figure C-8. Well Completion Diagram for Target Road South Drill Site

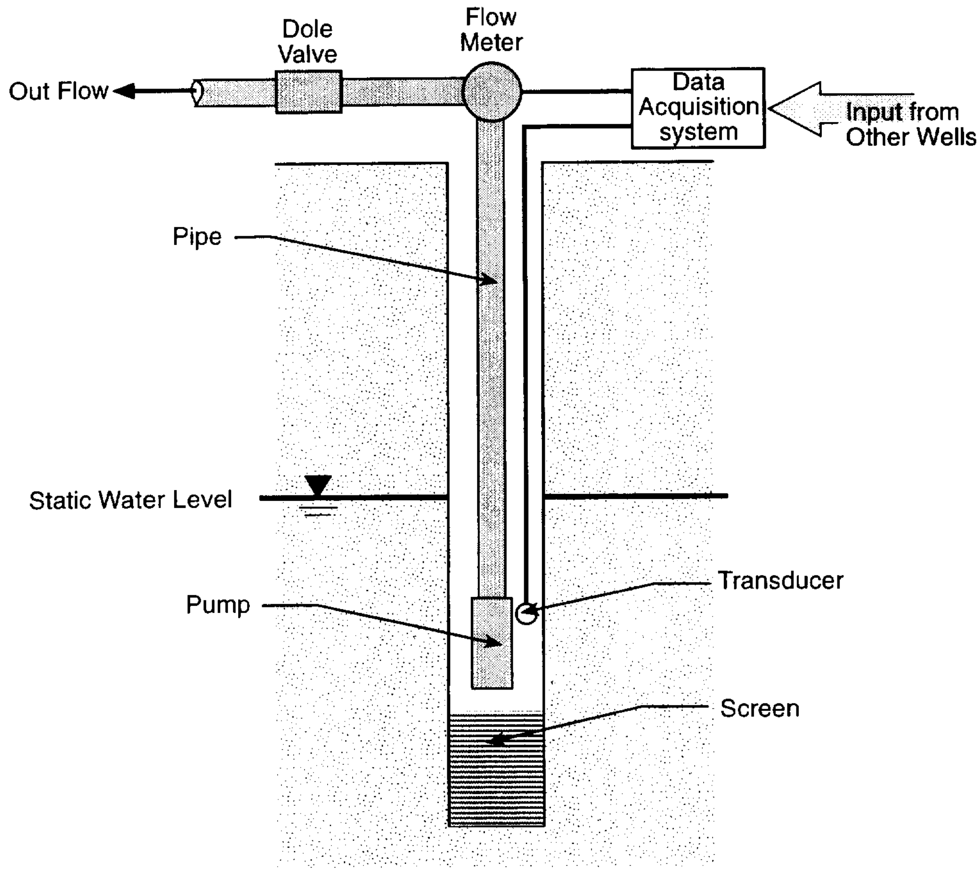


Figure D-1. Generic Aquifer Pumping Test System Layout

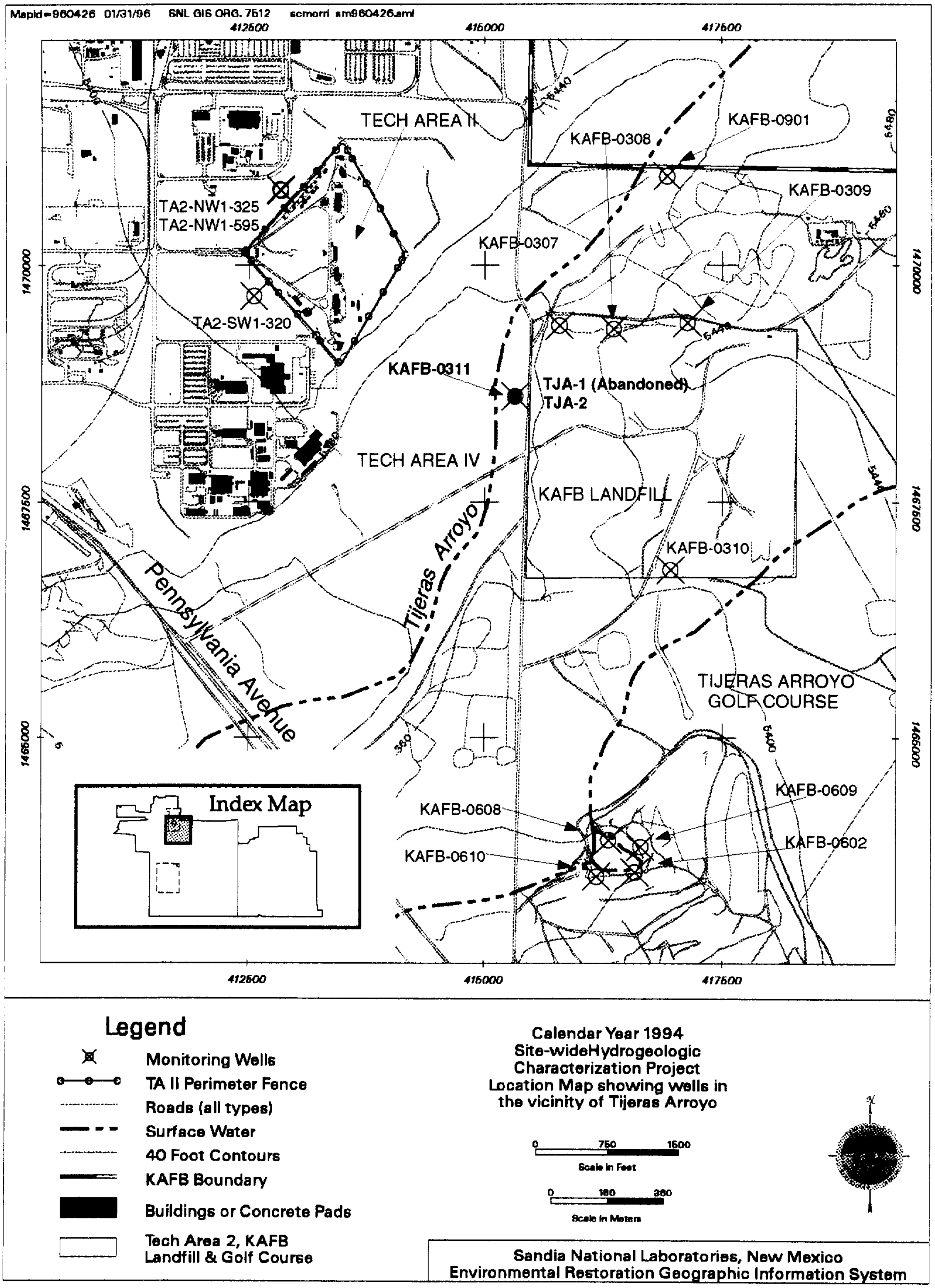


Figure D-2. Location Map for TJA-2 and KAFB-0311 Monitoring Test Wells

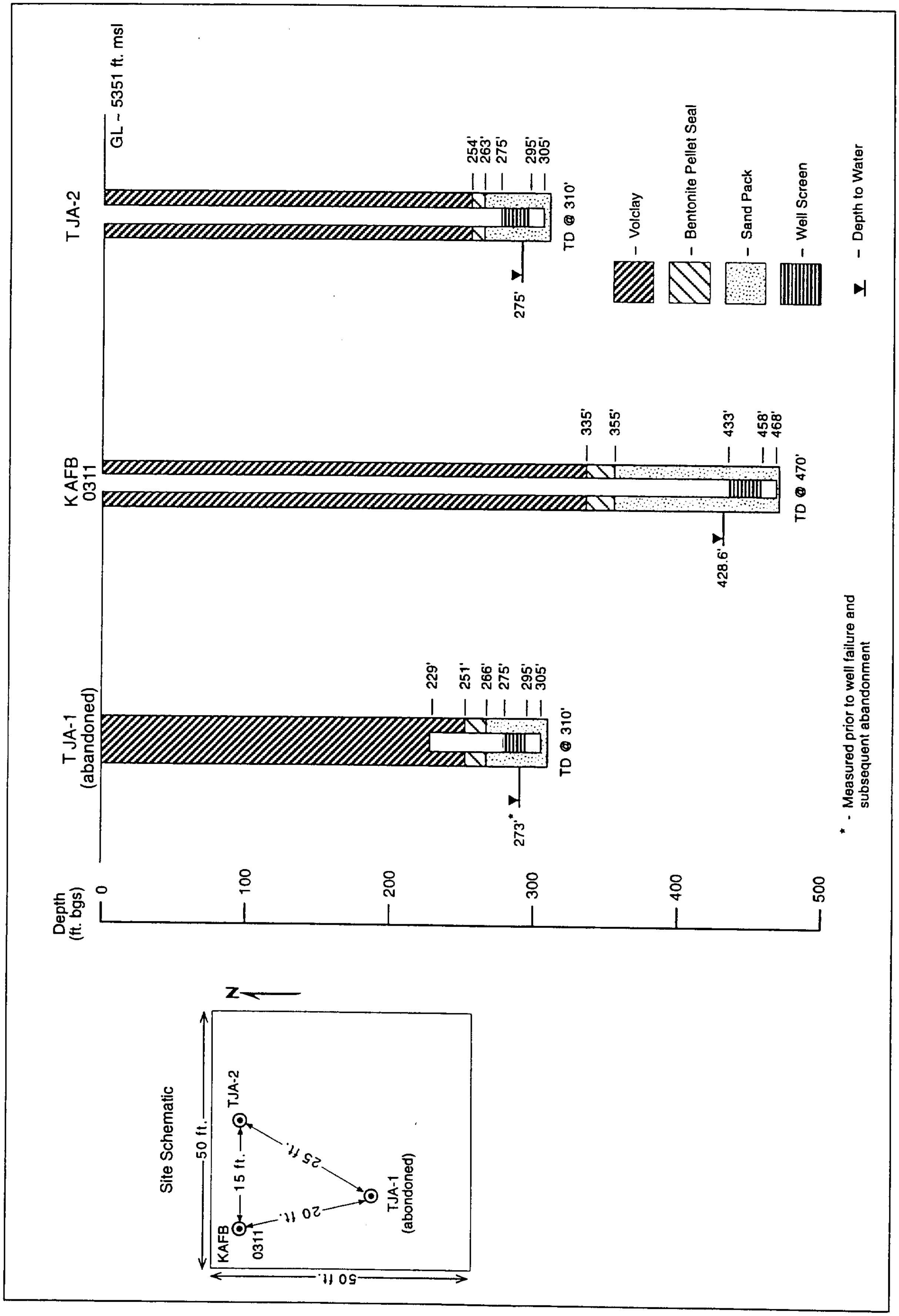


Figure D-3. TJA-2 and KAFB-0311 Well Site Schematic

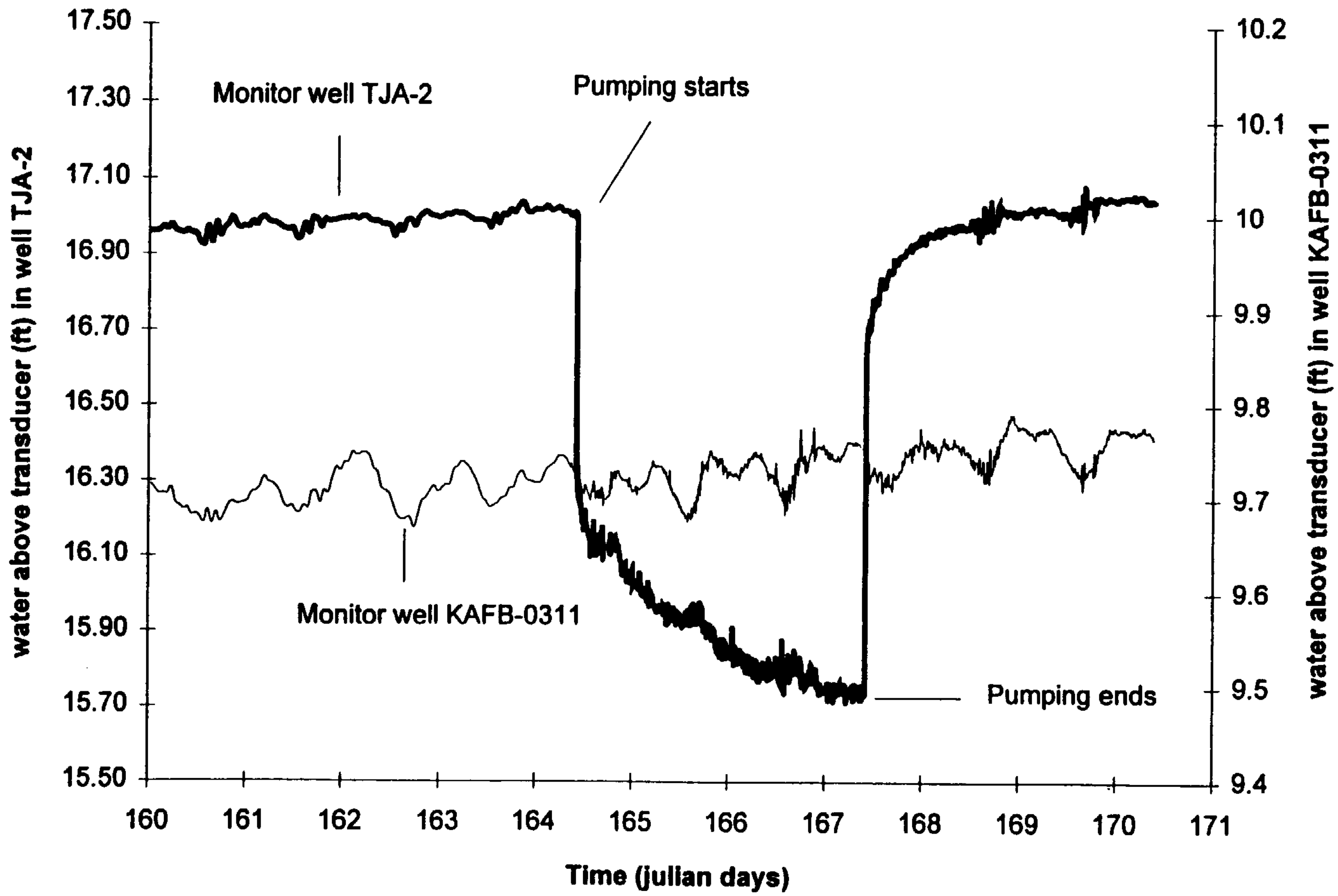


Figure D-4. Measured Water Levels in Test Well TJA-2 During Pumping and Recovery

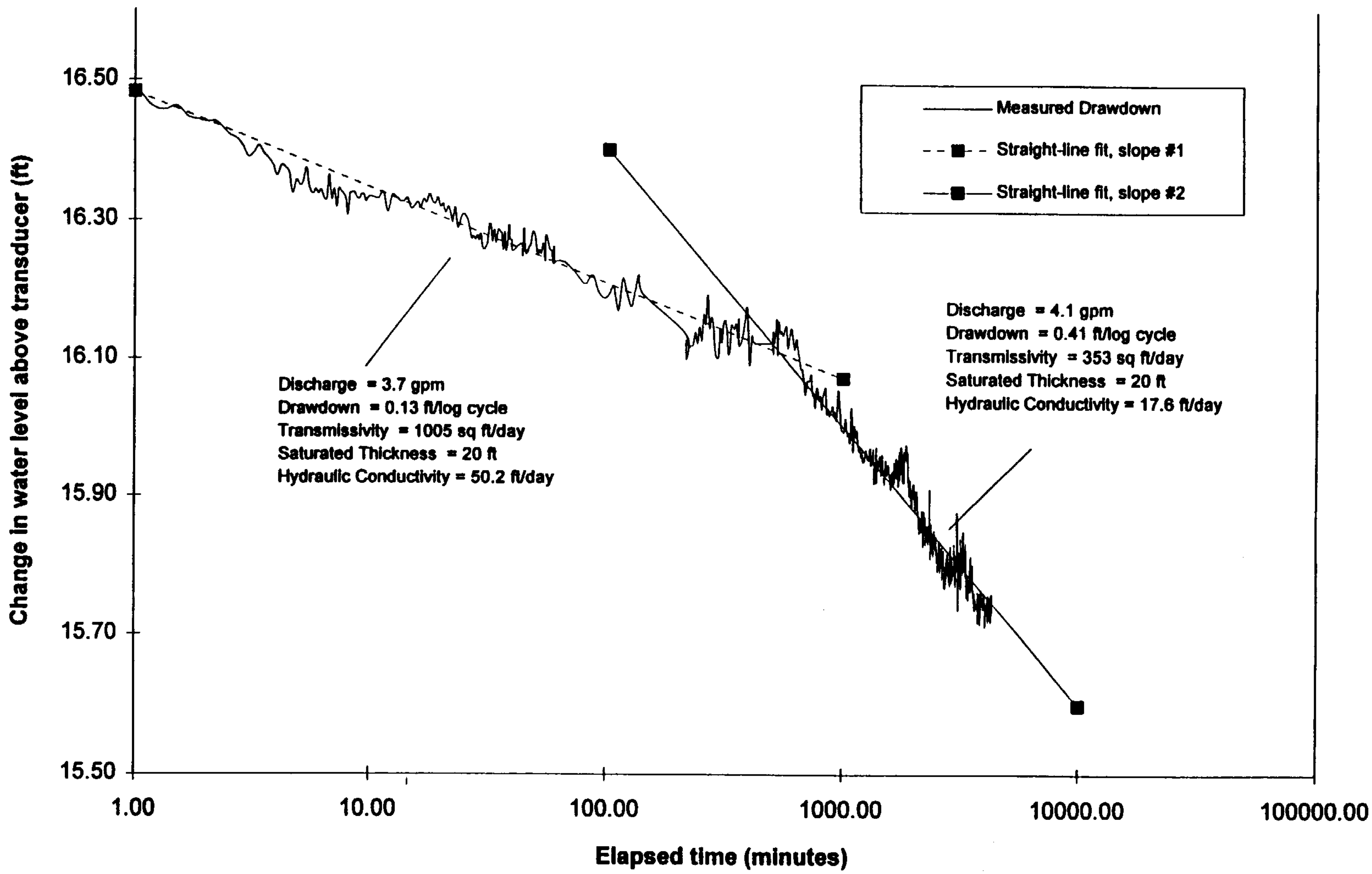


Figure D-5. Cooper Jacob Analysis of TJA-2 Drawdown Data

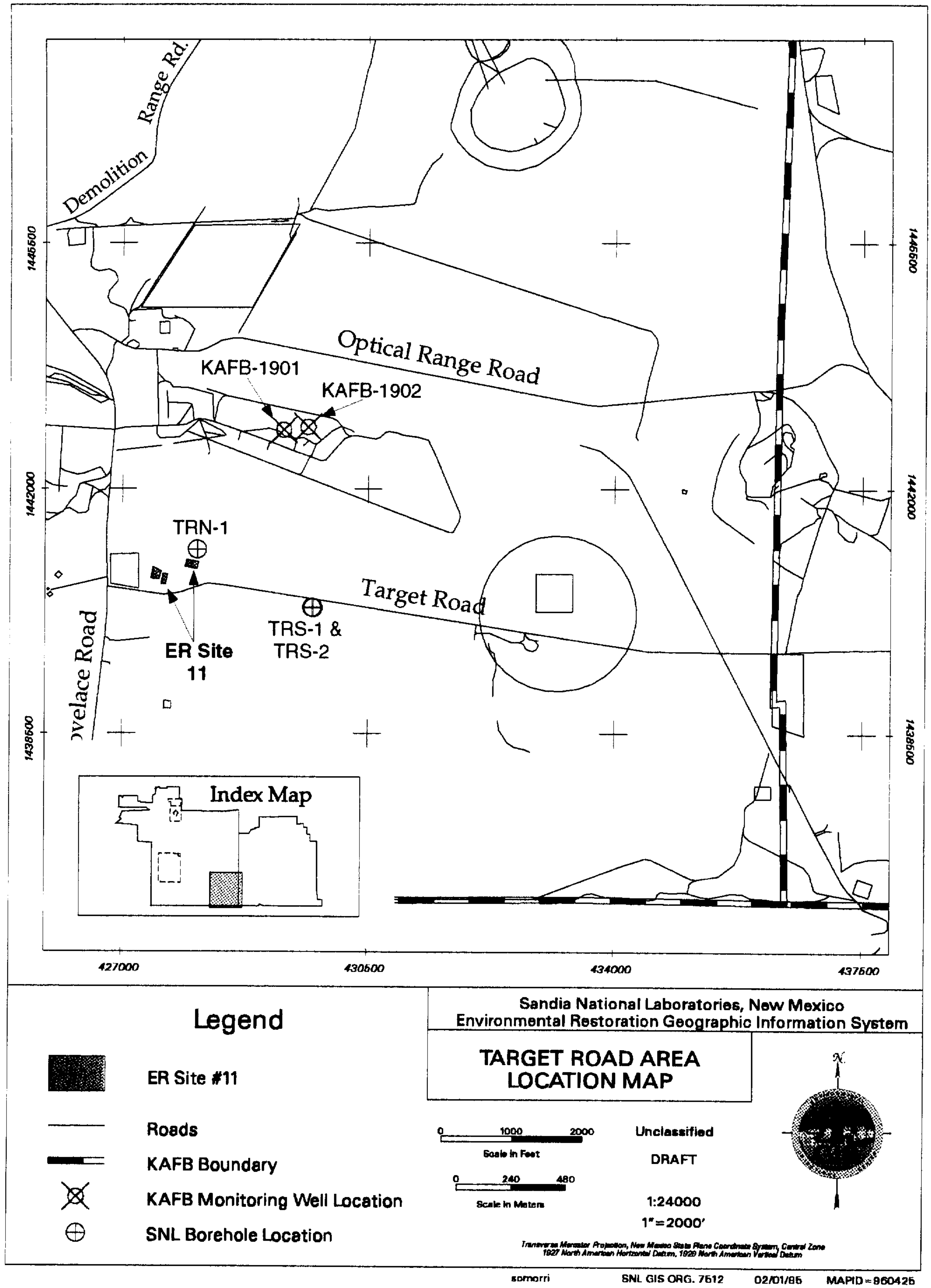


Figure D-6. Location Map for TRN-1 Monitoring Test Well

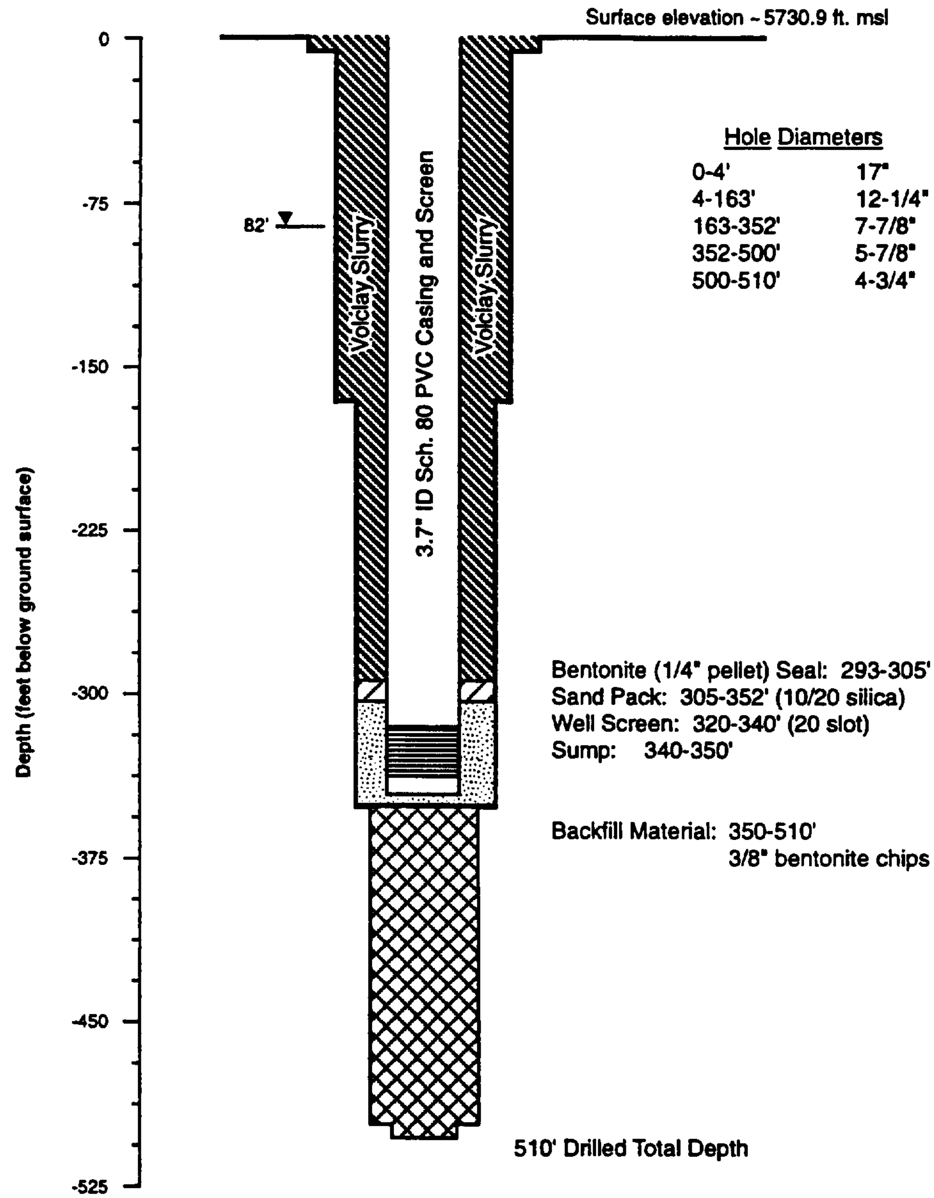


Figure D-7. TRN-1 Well Site Schematic

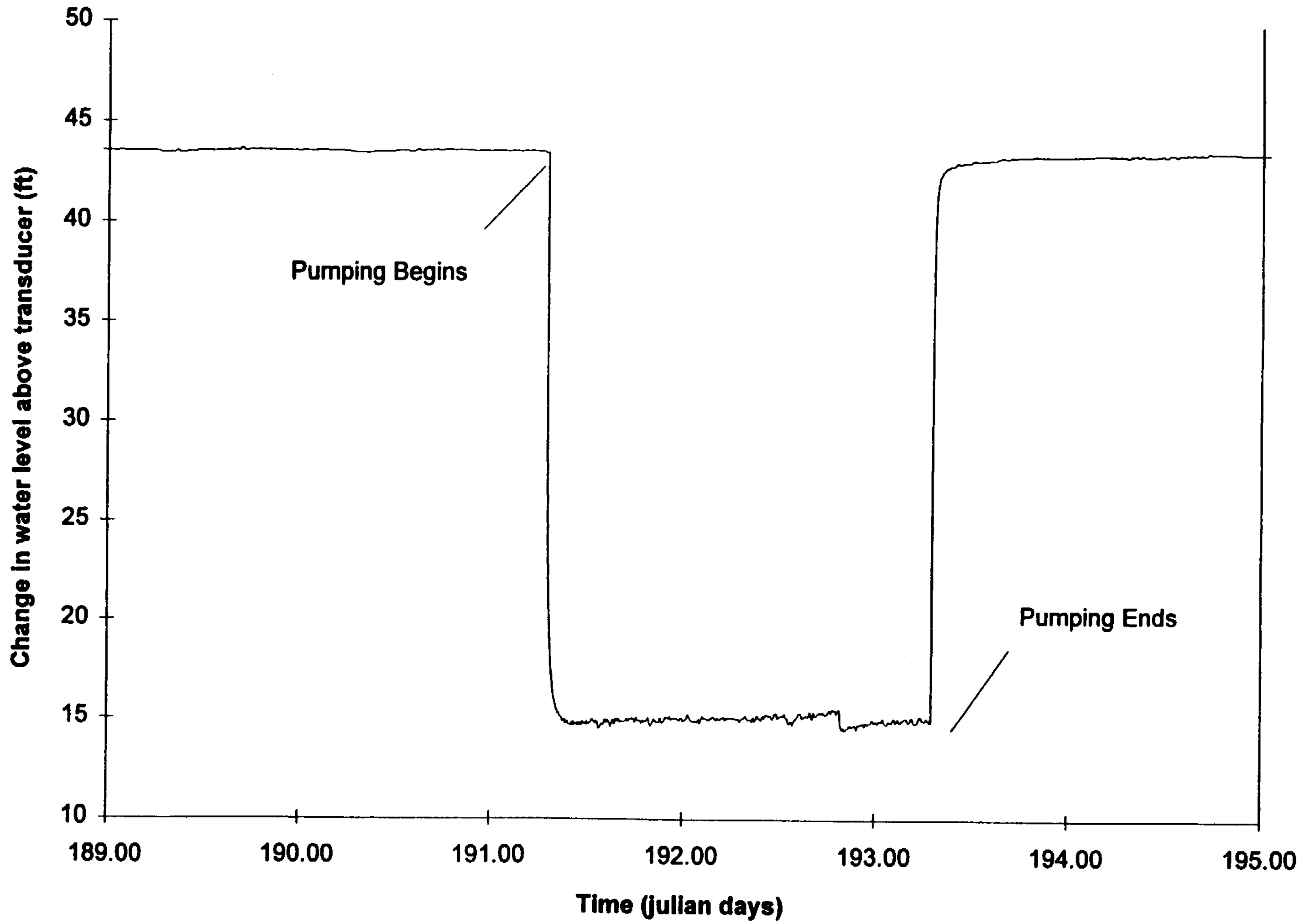


Figure D-8. Measured Water Levels in Test Well TRN-1 During Pumping and Recovery

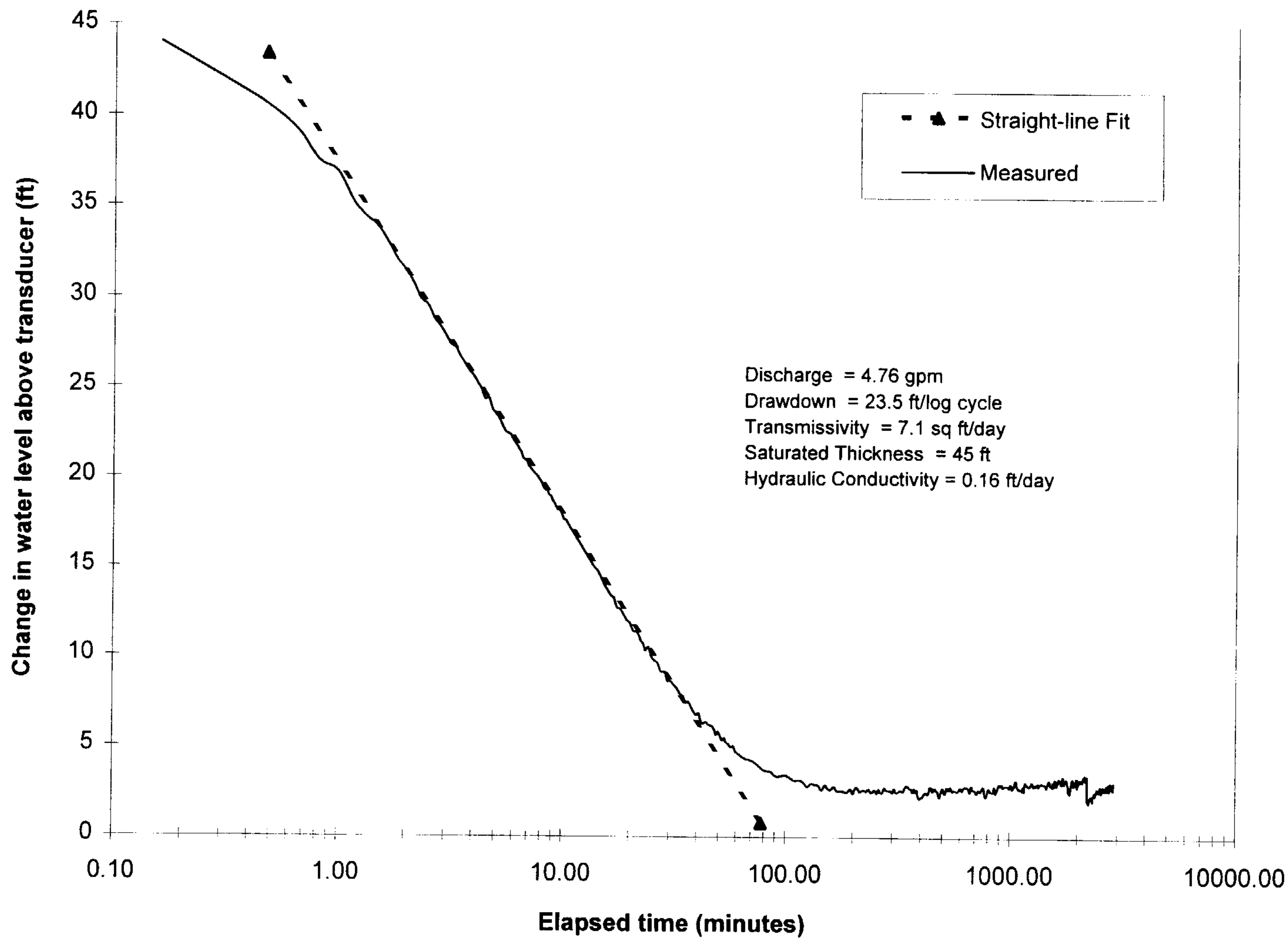


Figure D-9. Cooper Jacob Analysis of TRN-1 Drawdown Data

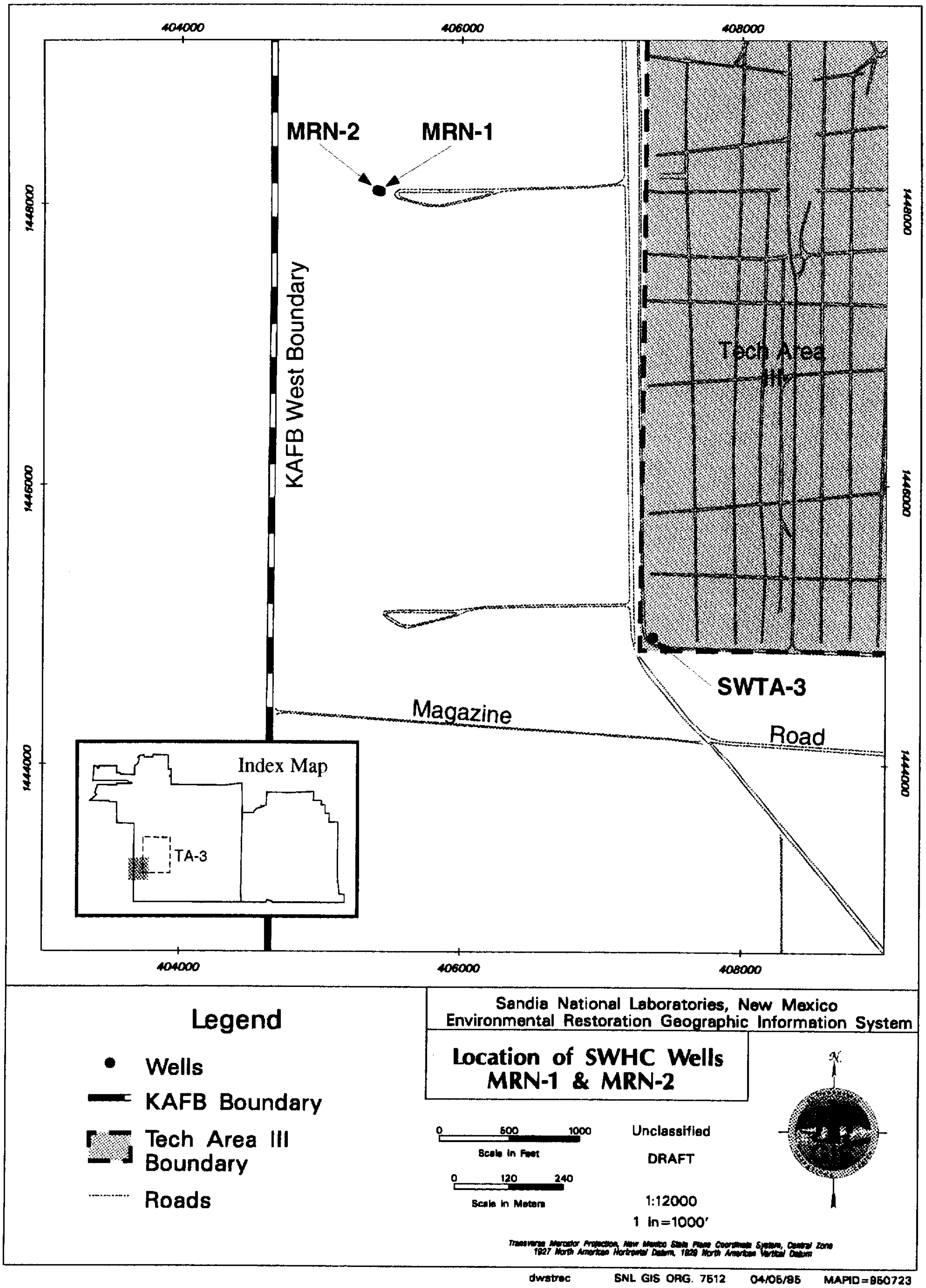


Figure D-10. Location Map for MRN-1 and MRN-2 Monitoring Test Wells

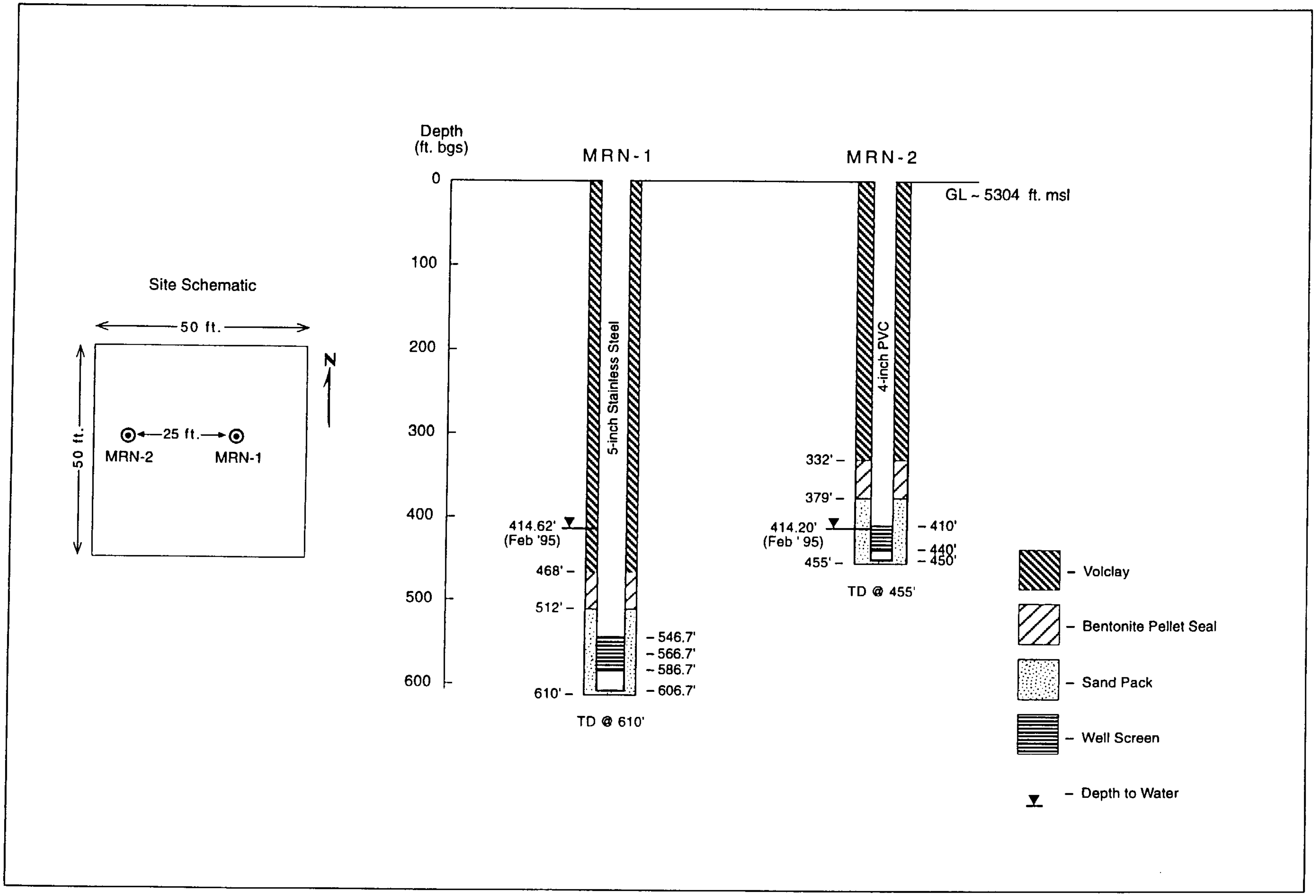


Figure D-11. MRN-1 and MRN-2 Well Site Schematic

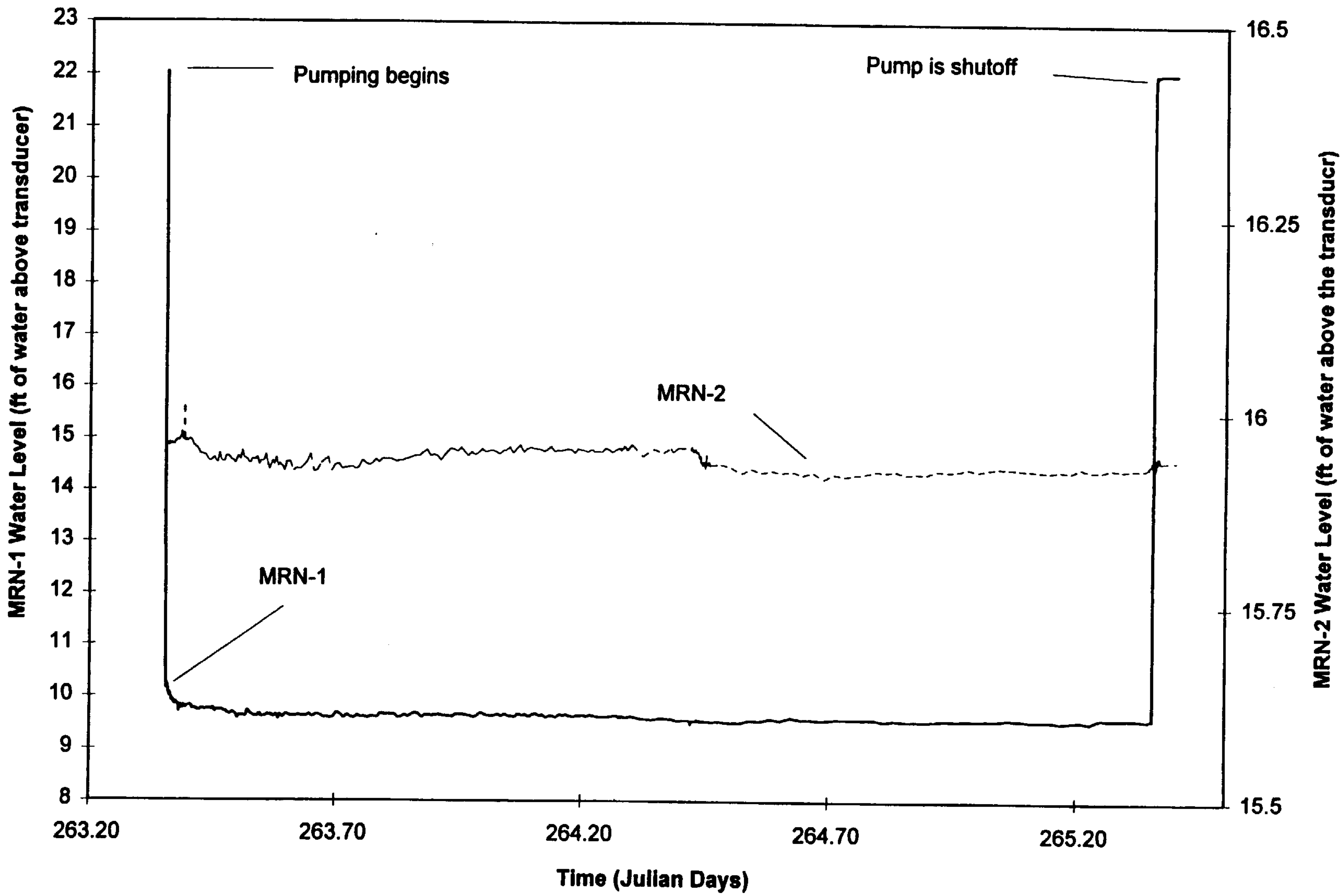


Figure D-12. Measured Water Levels in Test Well MRN-1 and Observation Well MRN-2 During Pumping and Recovery

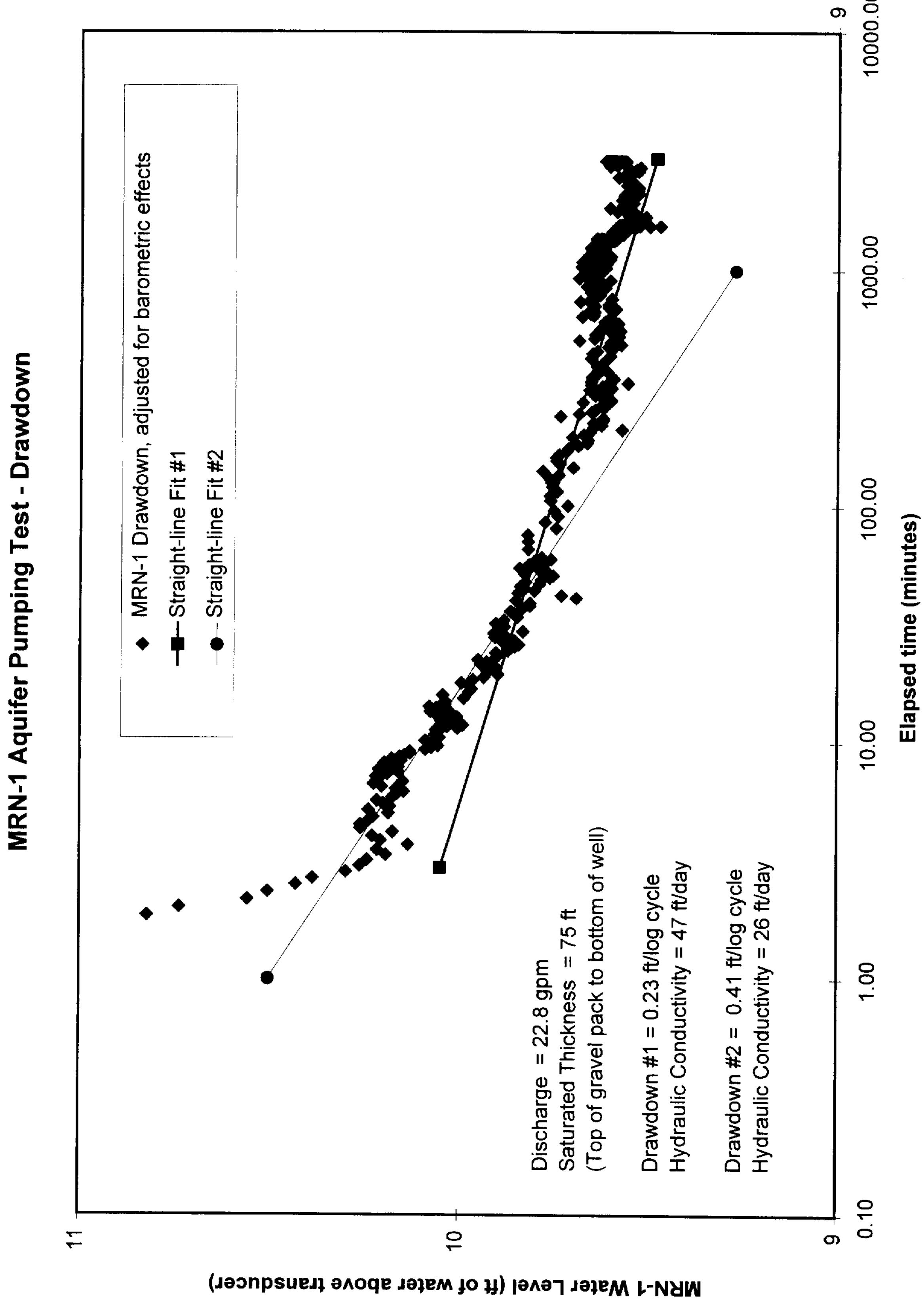


Figure D-13. Cooper Jacob Analysis of MRN-1 Drawdown Data

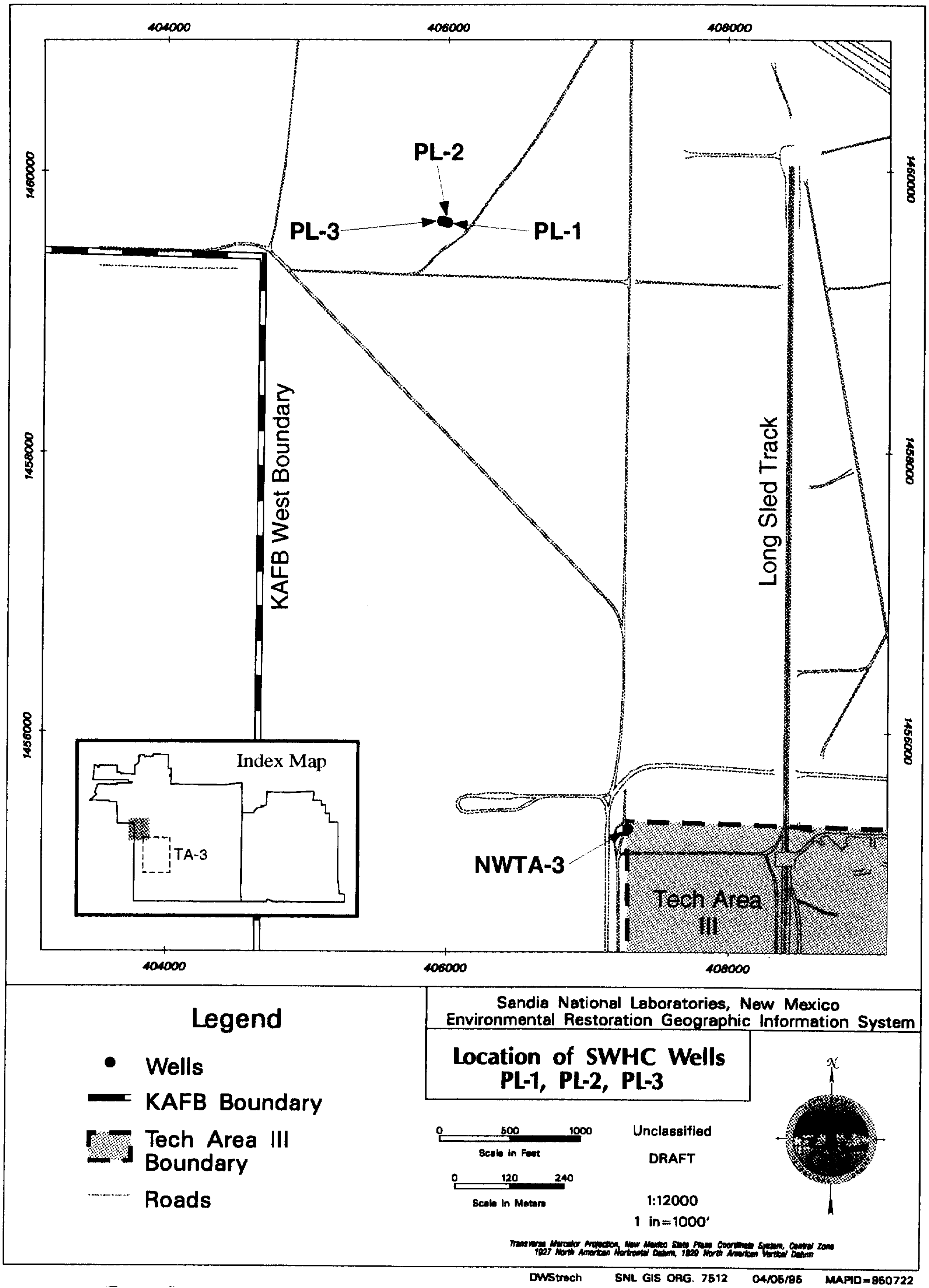


Figure D-14. Location Map for PL-1, PL-2, and PL-3 Monitoring Test Wells

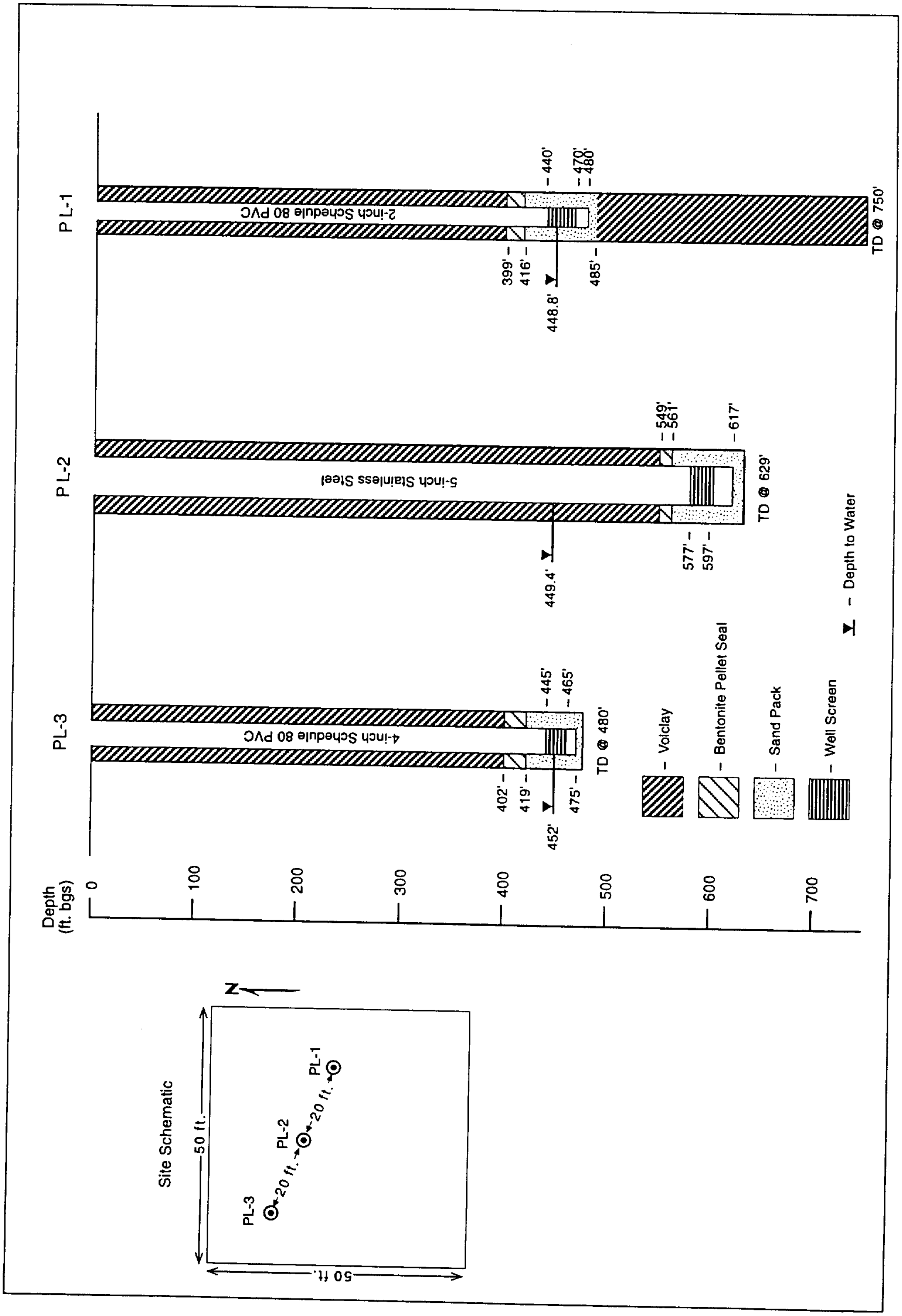


Figure D-15. PL-1, PL-2 and PL-3 Well Site Schematic

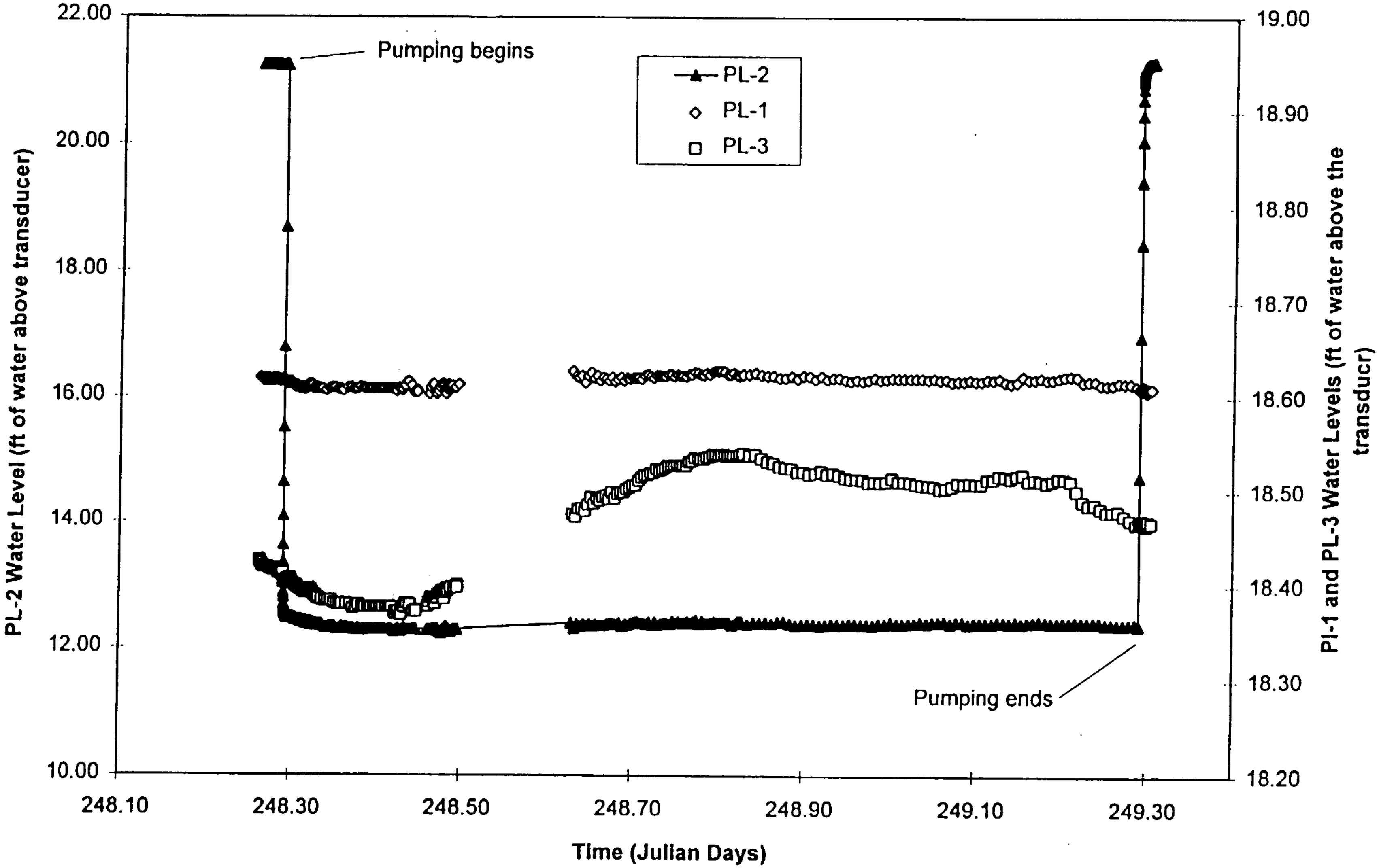


Figure D-16. Measured Water Levels in Test Well PL-2 and Observation Wells PL-1 and PL-3 During Pumping and Recovery (Note: A failure in the data acquisition system resulted in uncollected data between about 5 and 8 hours into the test.)

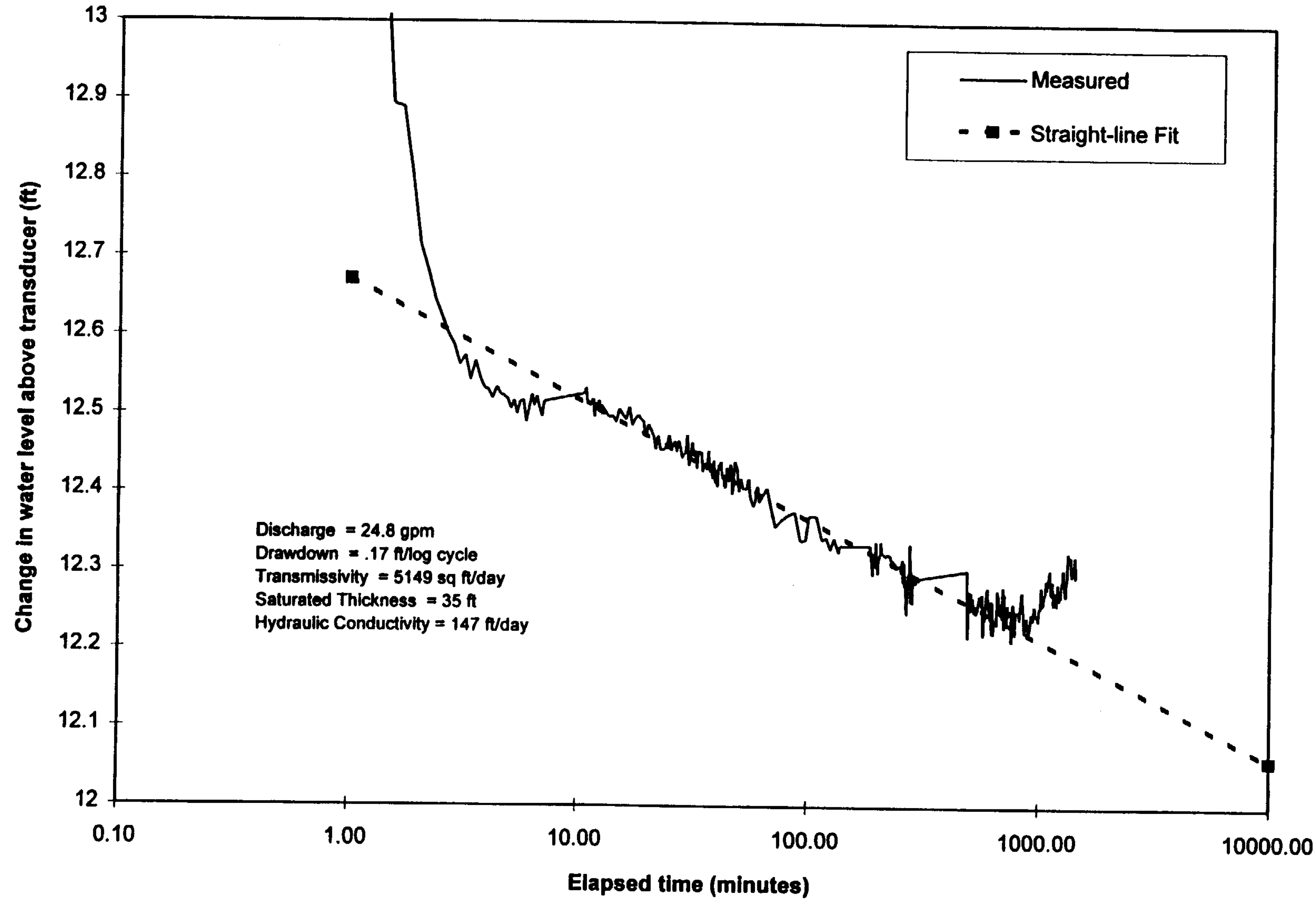


Figure D-17. Cooper Jacob Analysis of PL-2 Drawdown Data

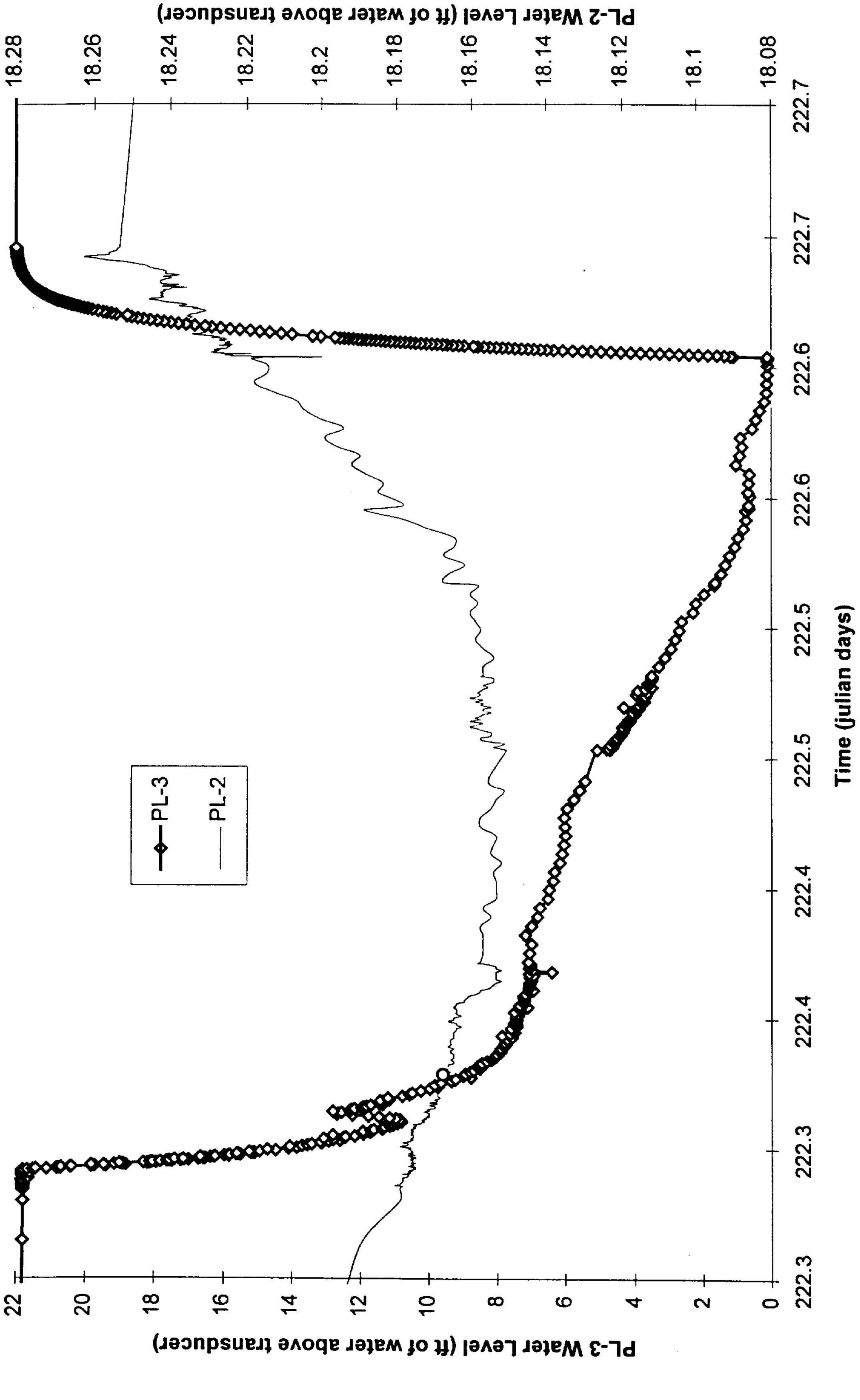


Figure D-18. Measured Water Levels in Test Well PL-3 During Pumping and Recovery

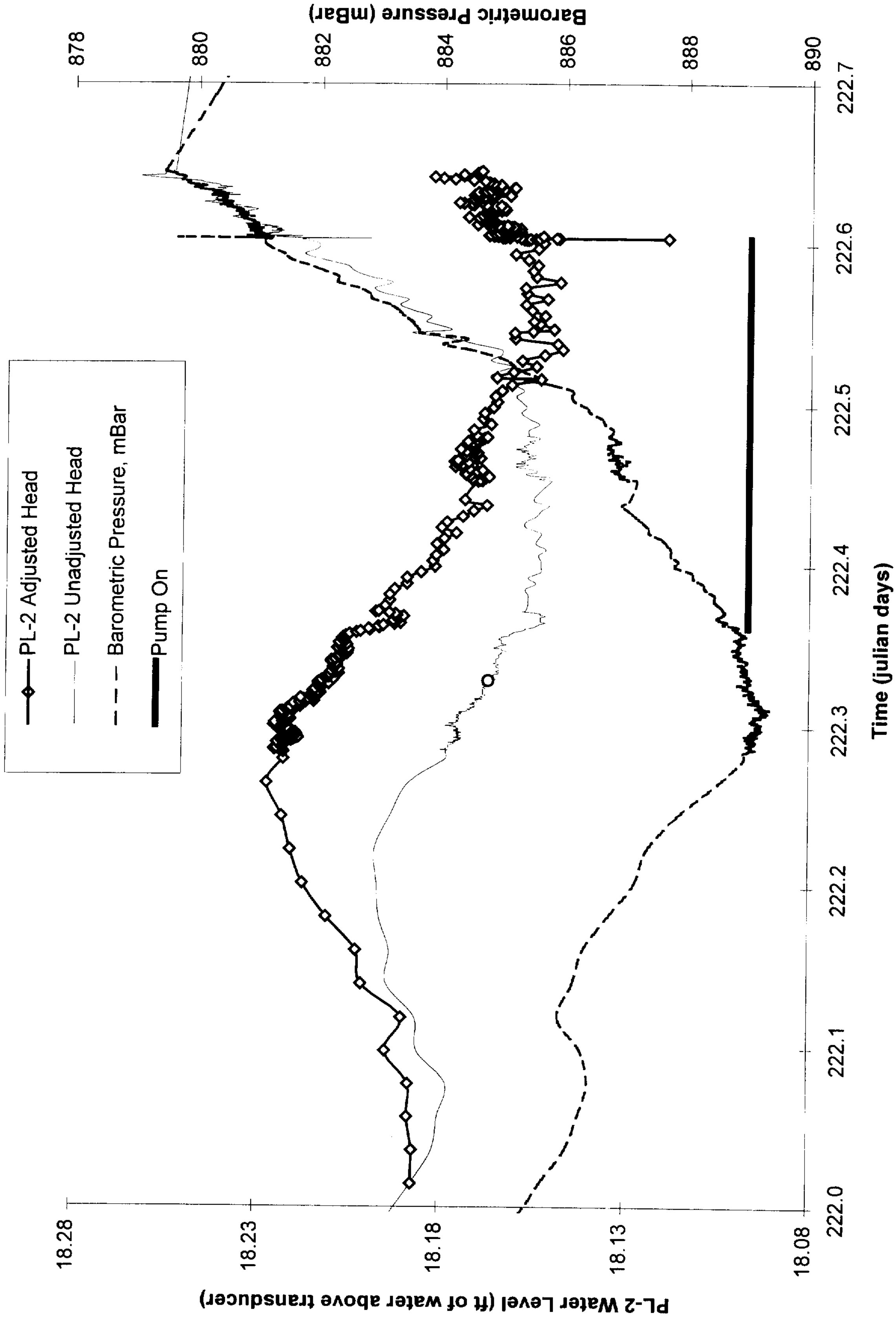


Figure D-19. Impact of Barometric Pressure on PL-2 Water Level During the PL-3 Aquifer Test

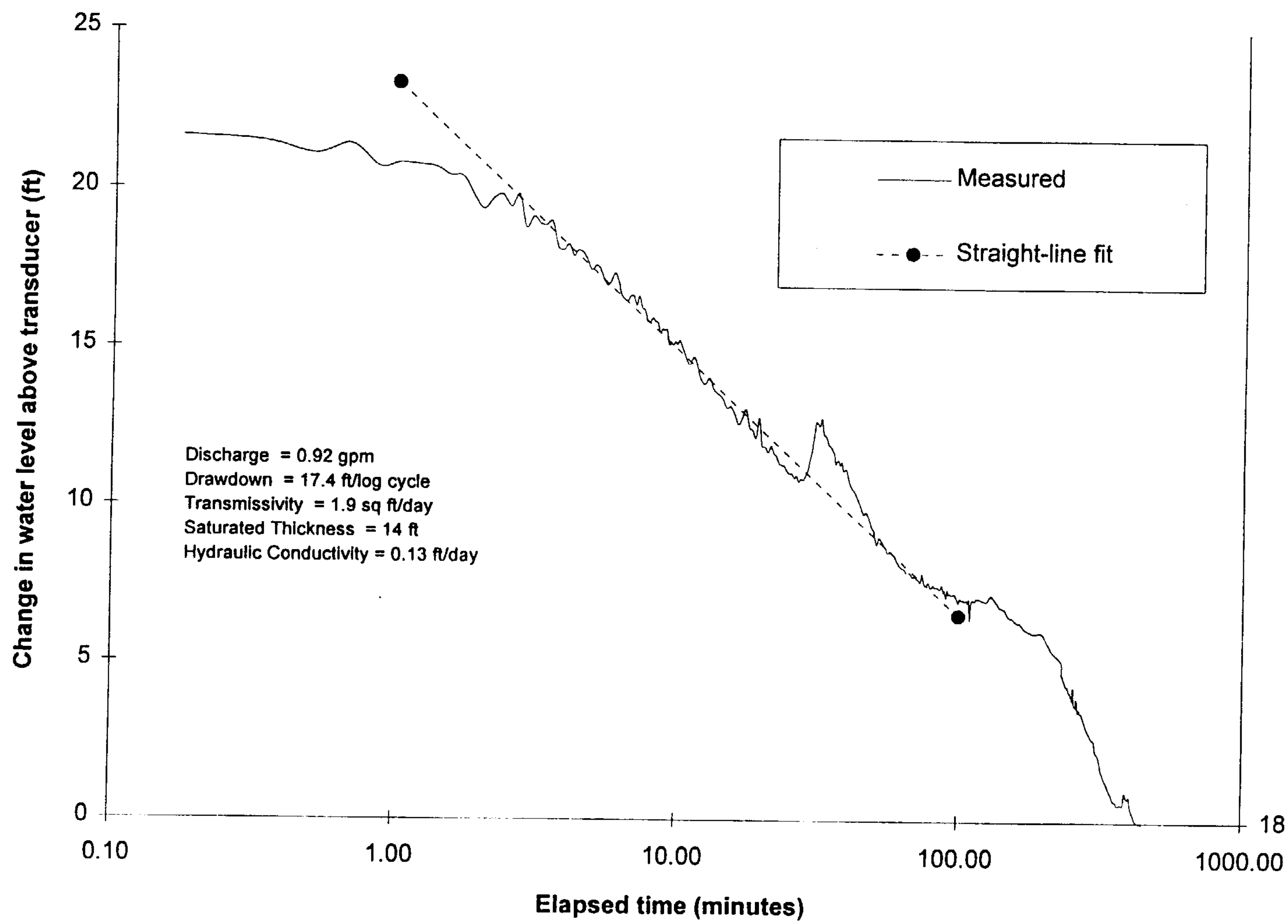


Figure D-20. Cooper Jacob Analysis of PL-3 Drawdown Data

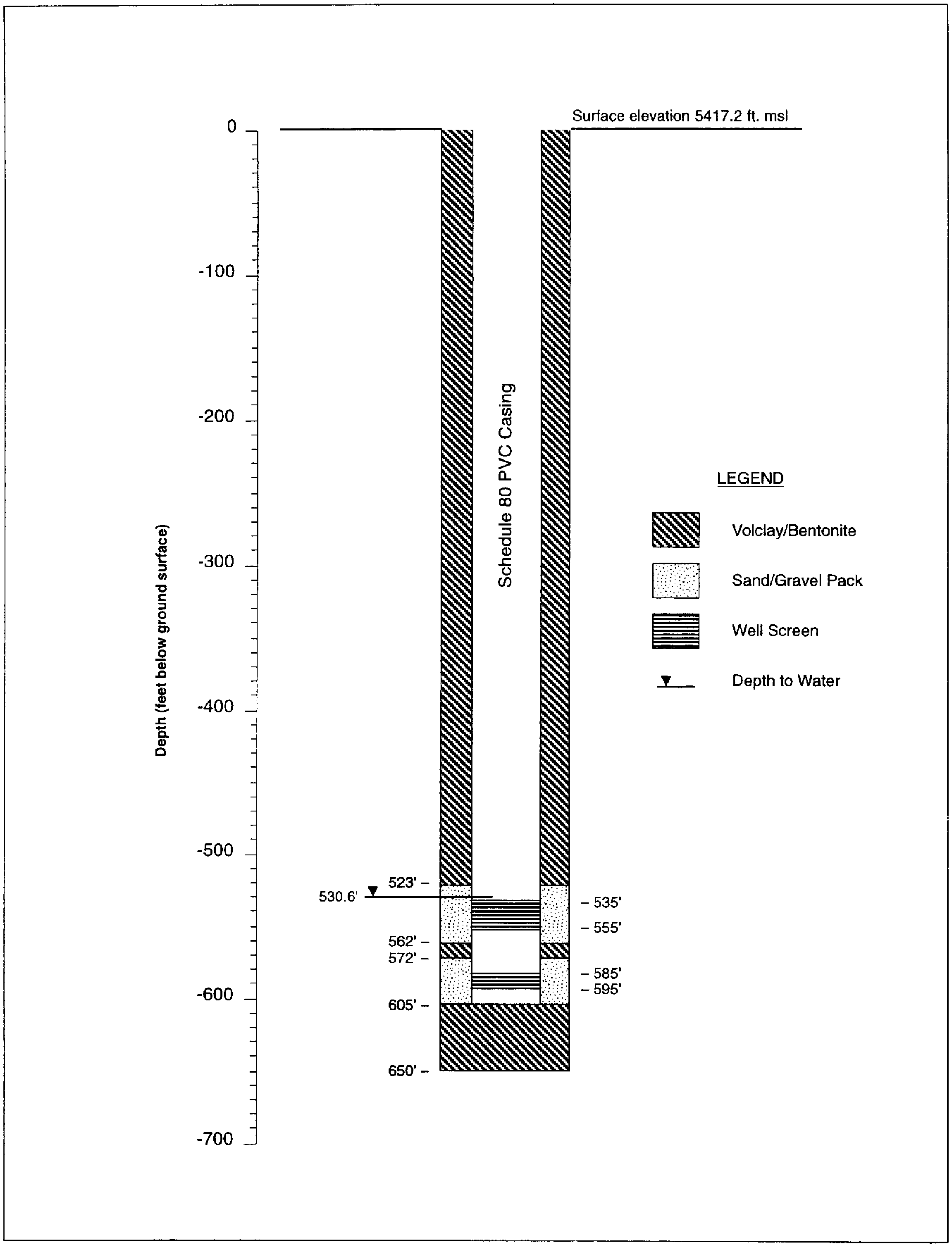


Figure D-21. Well Completion Schematic for Monitoring Well TA2-NW1-595

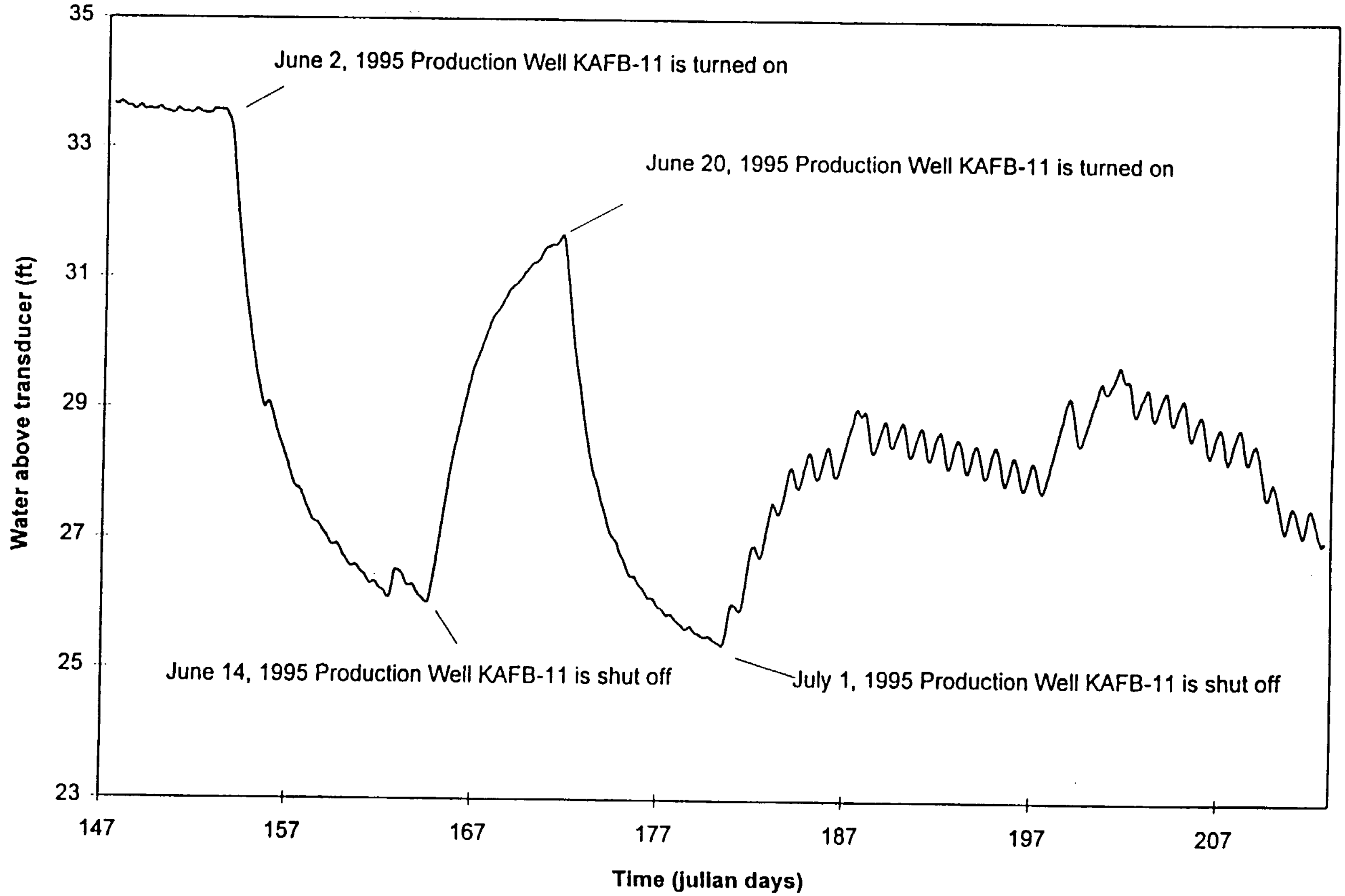


Figure D-22. Measured Water Levels in Test Well TA2/NW1/595 During Pumping and Recovery

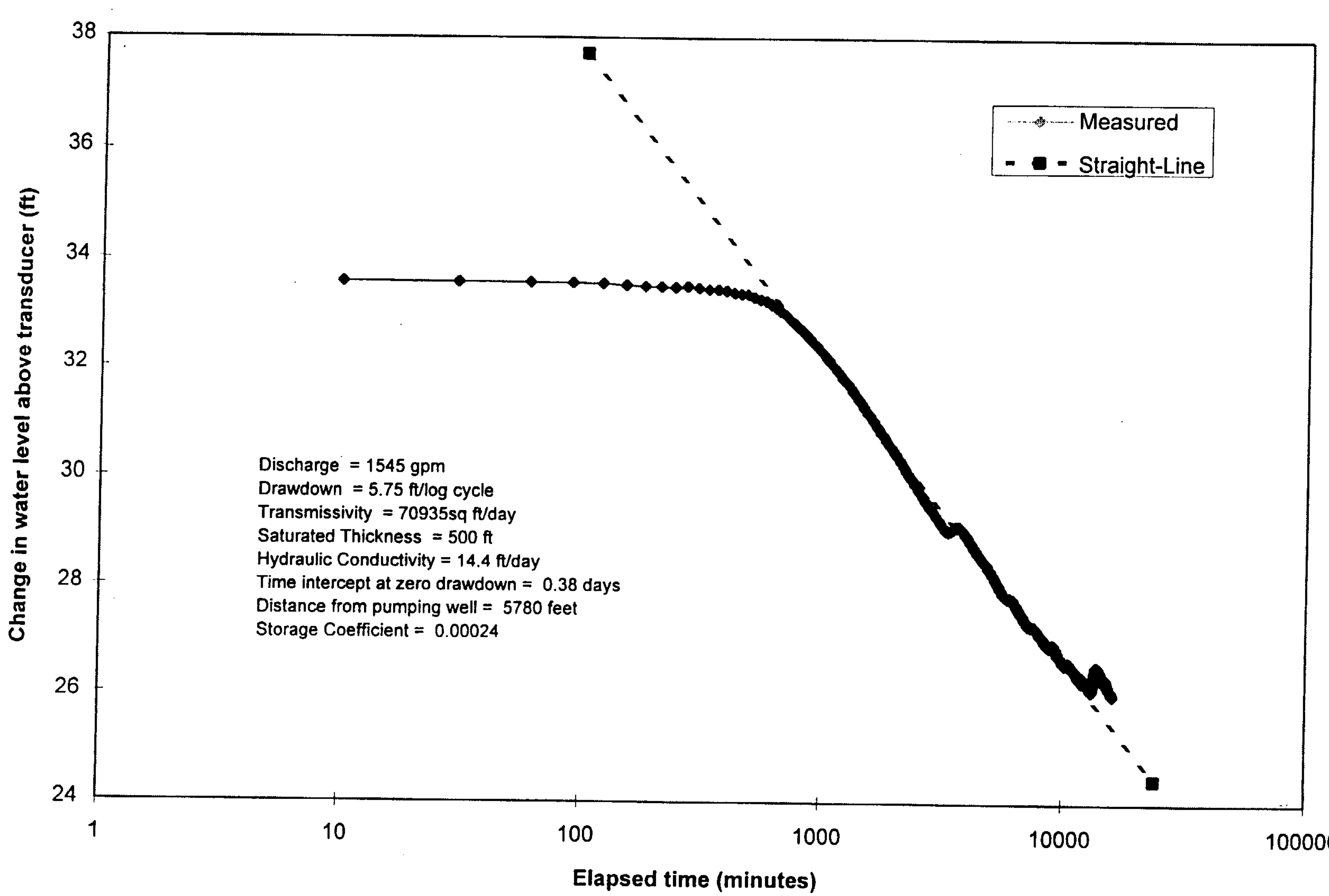


Figure D-23. Cooper Jacob (1946) Analysis of TA2-NW1-595 Drawdown Data for the Period June 2-14, 1995.

Attachments 1 –3 Errata

Attachment 1: Conceptual Geologic Model of the Sandia National Laboratories and Kirtland Air Force Base	
Revised Page or Figure	Reason for Revision
Page 2-9	Draft EPA Comment 11
Page 2-27	Draft EPA Comment 10a
Page 2-31	Draft EPA Comment 10b
Attachment 2: Geochemical Study of Groundwater at Sandia National Laboratories/New Mexico and Kirtland Air Force Base	
Revised Page or Figure	Reason for Revision
Page 2-4	NMED DOE/OB Hydrogeochemical Study (RUST Geotech) Technical Comment 1
Page 4-1	NMED DOE/OB Hydrogeochemical Study (RUST Geotech) Editorial Comment 2
Page 4-6	NMED DOE/OB Hydrogeochemical Study (RUST Geotech) Editorial Comment 2
Page C-1	NMED DOE/OB Hydrogeochemical Study (RUST Geotech) Editorial Comment 2
Attachment 3: Tijeras Arroyo Infiltration Experiment	
Revised Page or Figure	Reason for Revision
Page 8-1	NMED DOE/OB Tijeras Arroyo Infiltration Experiment Editorial Comment 2
Figures 7.7 – 7.10, 7.12-7.15, 7.17–7.20, and 7.22-7.30	NMED DOE/OB Tijeras Arroyo Infiltration Experiment Editorial Comment 1

The landform and depositional environment of a surficial deposit is designated by the second map unit modifier (e.g., alluvial fan [f], terrace [t], playa [pl]). This modifier provides information on probable sediment characteristics, including internal structure, clast size, and composition of the map unit. For example, eolian deposits and dunes (e.g., [e] or [d]) typically contain unbedded, well-sorted, quartz- or feldspar-rich silt and sand, whereas stream terrace deposits (e.g., [t]) typically contain thin to thick beds of coarse-grained to cobble-sized clasts of mixed composition.

Relative age is shown by the third modifier (e.g., oldest [1] or youngest [9]). This modifier provides an indication of the relative infiltration capacity of the surficial deposit. Infiltration capacities of most local soils are inversely proportional to the length of time during which the soil horizon was stabilized a few feet below the surface and subjected to the influence of climatic conditions (i.e., neither increasingly buried nor eroded away). The local climatic conditions are characterized by a rate of evaporation that greatly exceeds that of precipitation. Calcium salts in solution are transported a few feet into the soil by infiltration of rainwater before the water evaporates. The sources of the $CaCO_3$ are solution in rainwater, and $CaCO_3$ dust washed from the atmosphere or wind blown onto the surface. The salts precipitate and accumulate as $CaCO_3$ in the soil horizon and develop a whitish, crusty deposit called caliche. Given sufficient time the $CaCO_3$ accumulates to form a caliche with solid, concrete-like, relatively impermeable characteristics. Because the interpretation of the relative age of local soils is based mainly on the amount of caliche developed, it follows that interpreted soil age and anticipated infiltration characteristics are strongly correlated. For example, the Upper Llano de Manzano subprovince contains three distinct Pleistocene alluvial fans, which are denoted Pf4.lm, Pf5.lm, and Pf6.lm (Plate I). These fans are differentiated based on amount of surface dissection, tonal qualities on aerial photography, topographic position, and relative soil development. The oldest fan deposits, with the lowest potential for infiltration, are those within unit Pf4.lm and are partially buried by younger Pf5.lm and Pf6.lm deposits.

The fourth modifier indicates the geomorphic subprovince in which the map unit is located (e.g., Tijeras Arroyo [.ta], Manzano Base [Four Hills] [.fh] see Figure 1.4-6). For example, the map unit Pf4.lm designates Pleistocene alluvial-fan deposits within the Upper Llano de Manzano subprovince that are older than Pleistocene fan deposits within units Pf5.lm and Pf6.lm (Plate I). The fourth modifier also provides information on deposit composition. Surficial deposits, although they may be of similar age and within similar landforms (e.g., an alluvial fan), vary considerably in relative amounts of granitic, calcareous, sedimentary, and metamorphic clasts. For example, map unit Pf5.ta may be age-correlative with map unit Pf5.fh, but there are considerable differences in lithologic, soil, and geochemical properties between these two units. Surficial deposits in the Sandia Mountains, Eldorado, and Manzano Base (Four Hills) geomorphic subprovinces consist primarily of sediments derived from granitic rocks. Surfaces and associated deposits in the Manzanita Mountains and Upper Llano de Manzano geomorphic subprovinces consist primarily of sediments derived from schist, greenstone, limestone and quartzite of the Manzanita Mountains. Deposits in the Tijeras Arroyo subprovince likely contain all of these rock types, as well as sandstone and siltstone from the Tijeras Canyon drainage and sand, silt, and gravel derived from the poorly consolidated upper Santa Fe Group exposed in arroyo walls. Surficial deposits in the McCormick Ranch subprovince are derived primarily from local erosion of the Santa Fe Group and younger surficial deposits; thus they are probably quartz-rich sand, silt and clay. Surficial deposits in the Rio Grande province contain diverse lithologies from the Rio Grande drainage basin throughout northern New Mexico and southern Colorado.

Site-wide correlations between similar surficial deposits, shown in Figure 2.1-2, are based on: 1) height above active stream channels, 2) elevation similarities across subprovince boundaries, 3) geomorphic character (e.g., tonal contrast on aerial photography, amount of dissection, vegetation, genetic associations), 4) degree of soil-profile development and, where possible, the Santa Fe Group exposed in the southern wall of Tijeras Arroyo are undisplaced along the northern extension of the graben, showing that the faults do not extend as far as the arroyo.

The faults bounding the McCormick Ranch graben may influence groundwater movement as either barriers to or conduits for groundwater flow. The faults could be cemented with $CaCO_3$ and/or filled with crushed material. These conditions could impede westward movement of groundwater and allow drawdown of the groundwater trough to the east. Alternatively, but less likely, the faults could be zones of high permeability due to internal fracturing and could provide conduits for groundwater flow.

2.1.2.6 Four Hills Ranch fault

The Four Hills Ranch fault is a 2-mi- (3.2-km-) long northeast-trending fault along the southeastern margin of Tijeras Arroyo between SNL/KAFB and Tijeras Canyon (Plate I; Figure 2.1-3). The fault is named after a ranch located near the fault and shown on the USGS 1:24,000-scale Albuquerque East quadrangle map. Along the southeastern margin of Tijeras Arroyo upstream of its confluence with Arroyo del Coyote, several topographic saddles, linear drainages, and vegetation lineaments are interpreted as related to fault displacement. All of these features are present within middle Pleistocene alluvial-fan deposits (unit Pf3.lm, Plate I) . The southern end of the fault is at about the northern boundary of SNL/KAFB, where it enters the Holocene valley-fill deposits within the present-day arroyo. The fault may continue further to the southwest beneath the Holocene deposits within the arroyo. The northern end of the fault curves to a more easterly orientation and intersects the Sandia fault at the mouth of Tijeras Canyon (Figure 2.1-3, Plate I). Unpublished bedrock mapping by K. Karlstrom (University of New Mexico, written communication, 1995) shows the Four Hill Ranch fault truncated by the Sandia fault. His mapping also shows a west-trending fault strand parallel to the Four Hills Ranch fault, beneath Holocene deposits in Tijeras Arroyo. This strand coincides with a fault mapped by Kelley (1977) that offsets the surface trace of the Sandia fault in a right-lateral sense, and may be a strand of the Four Hills Ranch fault. If the Sandia fault is a west-dipping normal fault, this possible strand of the Four Hills Ranch fault could produce an apparent lateral offset by pure north-down dip-slip displacement.

The Four Hills Ranch fault potentially is significant to the hydrogeologic characterization of SNL/KAFB for two reasons. First, it is parallel to the present-day Tijeras Arroyo, suggesting that movement along the fault may have influenced the location of the arroyo. The arroyo trends to the west out of Tijeras Canyon, turns to the southwest upon encountering the fault, and then trends west again at the confluence of Arroyo del Coyote (Plate I). If there is a north-down strand of the Four Hills Ranch fault beneath the present-day arroyo, as suggested by previous bedrock mapping at the mouth of Tijeras Canyon (Kelley, 1977; K. Karlstrom, unpublished mapping, 1995), then movement along the fault may have controlled the location of the arroyo as it incised through the Pleistocene deposits. Erosion along the fault may have promoted laterally continuous bedding in TQsf deposits throughout the Tijeras Arroyo investigation area.

Overlying and inset into the TQsf deposits are middle Pleistocene alluvial-fan deposits derived from Tijeras Canyon (unit Pf3.ta, Plate III). These thick, laterally extensive deposits are also inset into middle Pleistocene fan deposits northwest of the Tijeras Arroyo investigation area (units Pf1.ta and Pf2.ta, Plate III). The Pf3.ta deposits are as much as 60 ft (18 m) thick near Pennsylvania Avenue (Figures 3.1-13 and 3.1-18),are thinner to the west, and are thicker to the east toward the mouth of Tijeras Canyon. The Pf3.ta deposits are poorly consolidated and typically contain interbedded fine-grained silty sand and sandy silt with minor, thin gravel beds. The fine-grained beds are moderately well sorted, whereas the gravel beds are poorly sorted and contain rare boulders. The deposits are exposed in both the northern and southern walls of Tijeras Arroyo and Arroyo del Coyote in the southeastern part of the investigation area (Plate III and Figure 2.1-5a). These exposures show the presence of several buried soil horizons within unit Pf3.ta, suggesting a complex depositional history for this large alluvial fan. The exposed deposits are similar to deposits penetrated by boreholes within the area (e.g., boreholes TA2-SW1-320 and KAFB-0608; Appendix B).

The geomorphic surface associated with the uppermost unit Pf3.ta deposits exhibits evidence of significant soil development, as shown by soils exposed in the arroyo walls and in soil pit SP10. This pit is located on the Pf3.ta alluvial fan surface on the southern side of Tijeras Arroyo, about 0.5 mi south of the KAFB landfill (Plate III). The pit location was chosen as representative of the Pf3.ta surface, which on the southern side of the arroyo is preserved as a moderately dissected remnant up to about 0.3 mi wide and 0.8 mi long. Appendix D provides the field description of this pit and laboratory data derived from samples taken from the soil. Figure 2.1-6 is a schematic diagram showing selected field and laboratory data from soil pits in the Tijeras Arroyo area, including soil pit SP10.

Overall, soil pit SP10 shows evidence of three episodes of deposition and surface stability, in the form of one relict soil developed in eolian deposits mantling the Pf3.ta deposits, and two buried soils developed in the Pf3.ta deposits. The lower buried soil extends from a depth of 42 in (106 cm) to the base of the pit (98 in [250 cm]), and is developed in a fining-upward alluvial deposit. The upper buried soil is developed in fine-grained alluvium comparable to the upper part of the lower soil. The deposits containing these soils are grouped as Pf3.ta deposits, based on the presence of multiple buried soils observed elsewhere in the Pf3.ta deposits. Both buried soils in SP10 exhibit stage III calcium carbonate morphology and a weight percent of $CaCO_3$ of

Table 2-2 (continued). Rejected Data

Sampling Location	Sampling Date	Reason for Rejection
Schoolhouse	July 1992	Low Cl
Sol se Mete Spring	March 1994	No field alkalinity
Sol se Mete Spring	December 1993	No field alkalinity
Sol se Mete Spring	July 1993	No field pH
Sol se Mete Spring	April 1993	Low field pH
SFR-1D	July 1993	No field alkalinity
SFR-2S	July 1993	No field alkalinity
SW-TA3 Well	July 1993	Low pH
SW-TA3 Well	April 1993	High pH
Tijeras East	August 1992	Low SO_4
MRN-1	April 1995	High turbidity
PL-2	April 1995	High turbidity

Major cation, major anion, and pH data were used to compute the equilibrium ion distributions and mineral saturation indices for each groundwater sample with the program PHREEQE (Parkhurst et al. 1980). Table 2-3 lists the thermodynamic data used in this investigation.

Groundwater temperatures ranged from 7 to 24 °C but were generally between 15 and 20 °C. PHREEQE computations were performed at 25 °C, the standard temperature at which free energy data are reported. The small size of the temperature corrections would not affect the interpretations in this study.

The cation/anion ratios calculated by PHREEQE were used to select the MRD. Table 2-4 presents the cation/anion ratios calculated by PHREEQE for the data sets that remained after eliminating those that are based on lack of data or "suspect data."

Cation/anion ratios will approximate 1.0 if all chemical analyses are accurate and all significant components are included. Deviations from 1.0 indicate that these conditions are not met. Therefore, the MRD consists of the data set from each location that has a cation/anion ratio closest to 1.0. The MRD are listed in Table 2-5. The database containing the complete set of data is a text file named sand.dat and is included as Appendix A.

Ionic strength values shown in Table 2-4 are those computed by PHREEQE using its extended Debye-Huckle theory and the MRD. Additional information about these calculations and the software can be obtained from the USGS through the internet (http://h2o.usgs.gov/software/).

4.0 Description of the Sandia/KAFB Site

This section summarizes the geology, surface-water hydrology, groundwater hydrology, groundwater geochemistry, and mineralogy as they pertain to the current project. More detailed descriptions are in Sandia/NM (1994b) and the references in that report. Figure 4-1 presents the stratigraphy of the site, and Figure 4-2 presents the geology of the Sandia/KAFB site and wells.

4.1 Geology

The Sandia/KAFB site lies in the boundary area between crystalline bedrock mountains (Manzanita Mountains) to the east and Tertiary/Quaternary basin fill to the west. Major northeast-southwest trending faults are characteristic of rifting (crustal extension) processes that formed the basin. The Manzanita Mountains are composed of Precambrian schist, gneiss, and granite that is capped by Paleozoic sediments. In the transition zone faults, exposed blocks of basement (such as the block of Madera Limestone exposed at EOD Hill) exposed indicate a complex structural history.

The basin fill is a thick (more than 14,500 feet) sequence of alluvial fans deposited from the eastern highlands and fluvial sediments from the Rio Grande. These deposits predominately consist of the Tertiary Santa Fe Group with a thin Quarternary alluvial cover. The sedimentary grains consist of quartz, clay, pumice fragments, and a wide variety of lithic fragments including granite, schist, greenstone, limestone, and clastics.

4.2 Surface-Water Hydrology

Groundwater is likely to be influenced by the Rio Grande, a major perennial north-to-south flowing stream located about 5 miles west of the site boundary. Much of the Rio Grande water is diverted into irrigation ditches. The Rio Grande loses water to the aquifer in the vicinity of SNL/KAFB (Yapp 1985). Two major arroyos (Tijeras and Coyote) drain the mountainous area in the eastern portion of the site to the Rio Grande. Because the valley receives only about 9 inches of precipitation per year and evapotranspiration is high, little vertical infiltration is expected into the Santa Fe Group. The Sandia/NM Site-Wide Project is collecting infiltration data to help determine if all or almost all the vertical recharge into the basin fill is from arroyos during flood stages.

As much as 30 inches of precipitation falls in the mountains east of the SNL/KAFB site. The higher precipitation and lower evapotranspiration are likely to producc greater infiltration and groundwater recharge in the mountains than in the valley.

4.3 Groundwater Hydrology

Figure 4-3 shows a potentiometric map of the groundwater for the Sandia/KAFB site. Data for this map are from wells with screens in a variety of geologic units. Although the map is probably an accurate portrayal of the regional water table, local perturbances are likely. Regionally, groundwater flows from highlands toward the valley floor; east to west across the site. Groundwater also flows easterly from the Rio Grande. Pumping from the Santa Fe Group aquifer for the City of Albuquerque causes the cone of depression seen in the 4900-foot contour on Figure 4-3. This pumping adds a northwest component to the groundwater flow direction at the site.

4.4 Groundwater Major-Ion Geochemistry

Figure 4-4 is a Piper diagram of the MRD for the Sandia/KAFB site. Piper diagrams plot concentration ratios, expressed in milliequivalents (meq) per liter of major dissolved ions, and are useful for classifying groundwaters. Each groundwater analysis is plotted on a cation triangle, an anion triangle, and a diamond-shaped cation-plus-anion plot. The cation (Ca, Mg, and Na plus K) triangle is divided into four equivalent triangles. Points falling into the apical triangles are said to be dominated by that cation, whereas those in the center do not portray a particular dominance. The anion triangle is also divided into four equivalent triangles. Clusters of data may indicate similar origins. Data presented in Figure 4-4 indicate that most of the groundwater at the Sandia/KAFB site is calcium-bicarbonate type. Groundwater from KAFB-10 is sodium-chloride type and from SFR-3T is calcium/sodium-sulfate type.

The spatial distribution of Cl is shown as a spot plot in Figure 4-5. The size f the spot indicates the concentration of Cl at that location. Each spot is labeled with the concentration in milligrams per liter. All wells west of Hubbell Springs Fault are screened in the Santa Fe Group, while those east of the fault are screened in a variety of formations (Table 2-1). Figure 4-6 shows the distribution of Cl concentrations for only those wells that are screened in the Santa Fe Group. The distribution of Cl indicates relatively high concentrations in the Santa Fe Group near the faults, with progressively lower concentrations in the basin to the west. Because two of the wells (KAFB-10 and CWL-BW2) with particularly high Cl concentrations were screened at greater depths (Table 2-1) than other wells, Cl concentrations may be contributed from the deep basin. High Cl concentrations in KAFB-10 may be due to sampling problems; the well was sampled without purging (verbal communication with F. Lauffer).

Samples from the EOD Hill well and Coyote Springs display elevated Cl concentrations (Figure 4-5). These two sampling locations also have elevated concentrations of Ca, Na, C, Mg, K, Br, and ionic strength (Appendix C and Table 2-5). As indicated on the Stiff diagrams in Figure 4-7, the groundwater composition of the EOD Hill well is similar to Coyote Springs except for concentrations of Ca and HCO_3. Stiff diagrams provide a graphical display of multiple-ion concentrations that are absolute values, unlike Piper diagrams which are ratios.

Appendix C

Chemical Spot Plots for the Most Representative Data for All Wells and Springs (in alphabetical order)

Note:
Round or square spot sizes are proportional to observed concentrations. Negative values for saturation indices indicate concentrations less than saturation (i.e., mineral dissolution is possible), while positive saturation indices indicate super-saturation (i.e., mineral precipitation is possible). Negative values for isotopic ratios indicate water isotopically lighter than ocean water. Negative values for species concentrations indicate analytical errors and presumably very low concentrations.

8.0 SUMMARY AND CONCLUSIONS

The Tijeras Arroyo Infiltration Experiment (TAIE) was designed to monitor vadose response to an intermediate-scale ponded infiltration event. The TAIE is analogous to infiltration events where the vadose zone is contaminated through intermediate-sized effluent discharge scenarios.

TAIE accomplishments include: 1) implementation of the infiltration test, 2) mapping of the geology underlying the site, 3) determination of hydraulic properties of soil samples collected at the site, and 4) completing numerical simulations incorporating non-hysteretic and hysteretic conditions.

Based on the data presented in this report, some general conclusions can be made concerning equipment performance and vadose zone response.

Conclusions regarding equipment performance include the following: The data acquisition equipment performed well and provides useful information on flow rates, wetting front advancement, and changes in soil tensions during the redistribution phase of the test. Although the TDR data acquisition systems operated correctly and provided a detailed record of wetting front arrival times, anomalous readings did occur making moisture content data suspect.

Some conclusions have been reached concerning the vadose zone's response. Neutron data suggest that the lateral movement of the wetted bulb is slightly greater than its downward movement. In addition, the lateral spread of the wetted bulb was more extensive in a coarse-textured layer that is sandwiched between two finer textured layers. Numerical simulations of homogenous soils using textbook values of hydraulic properties can misrepresent true conditions. However, when hydraulic properties from the undisturbed sample were used, the computed wetting front advancement was more similar to the observed wetting front.

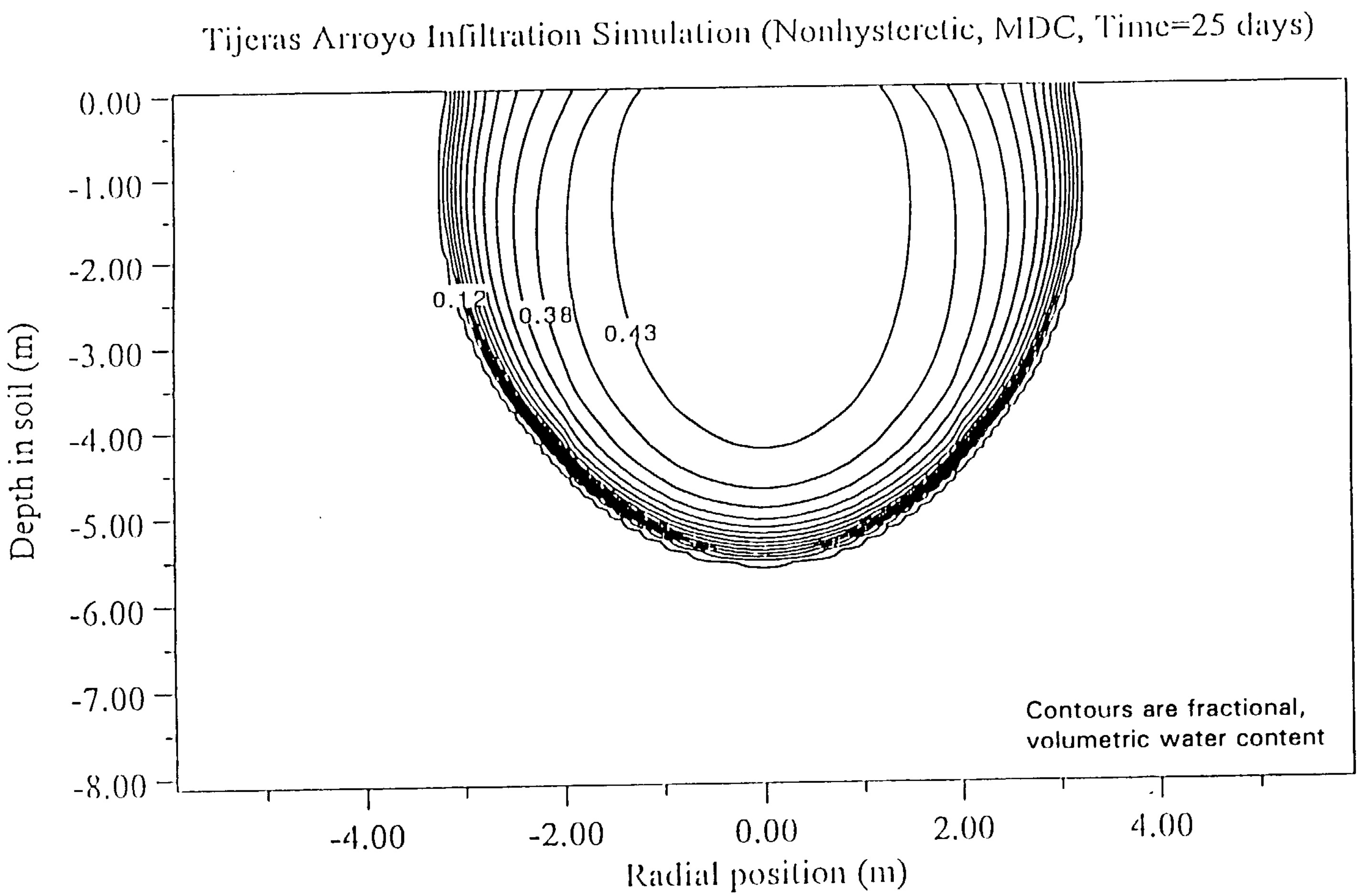


Figure 7.7: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MDC, Time = 25 days)

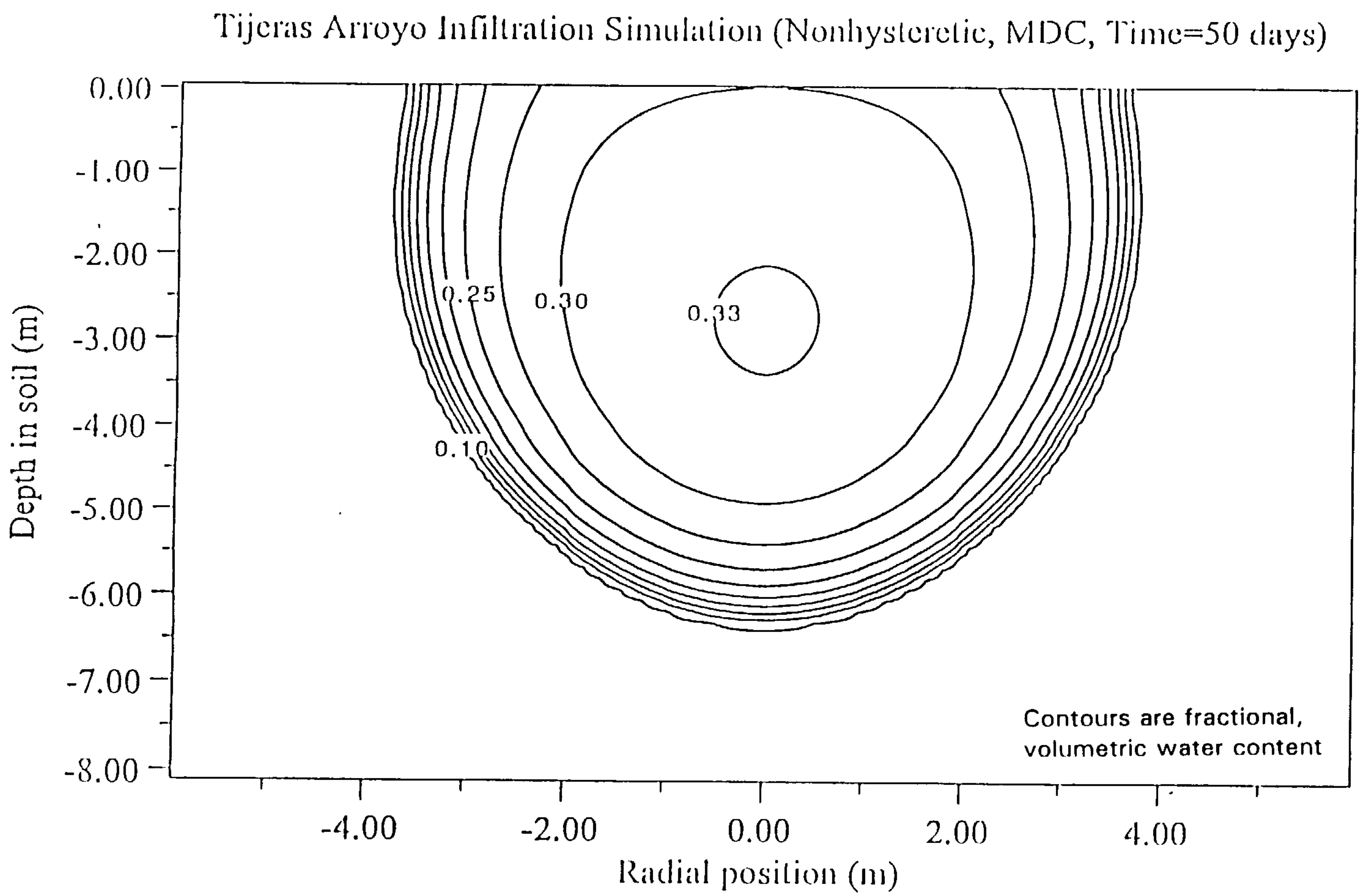


Figure 7.8: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MDC, Time = 50 days)

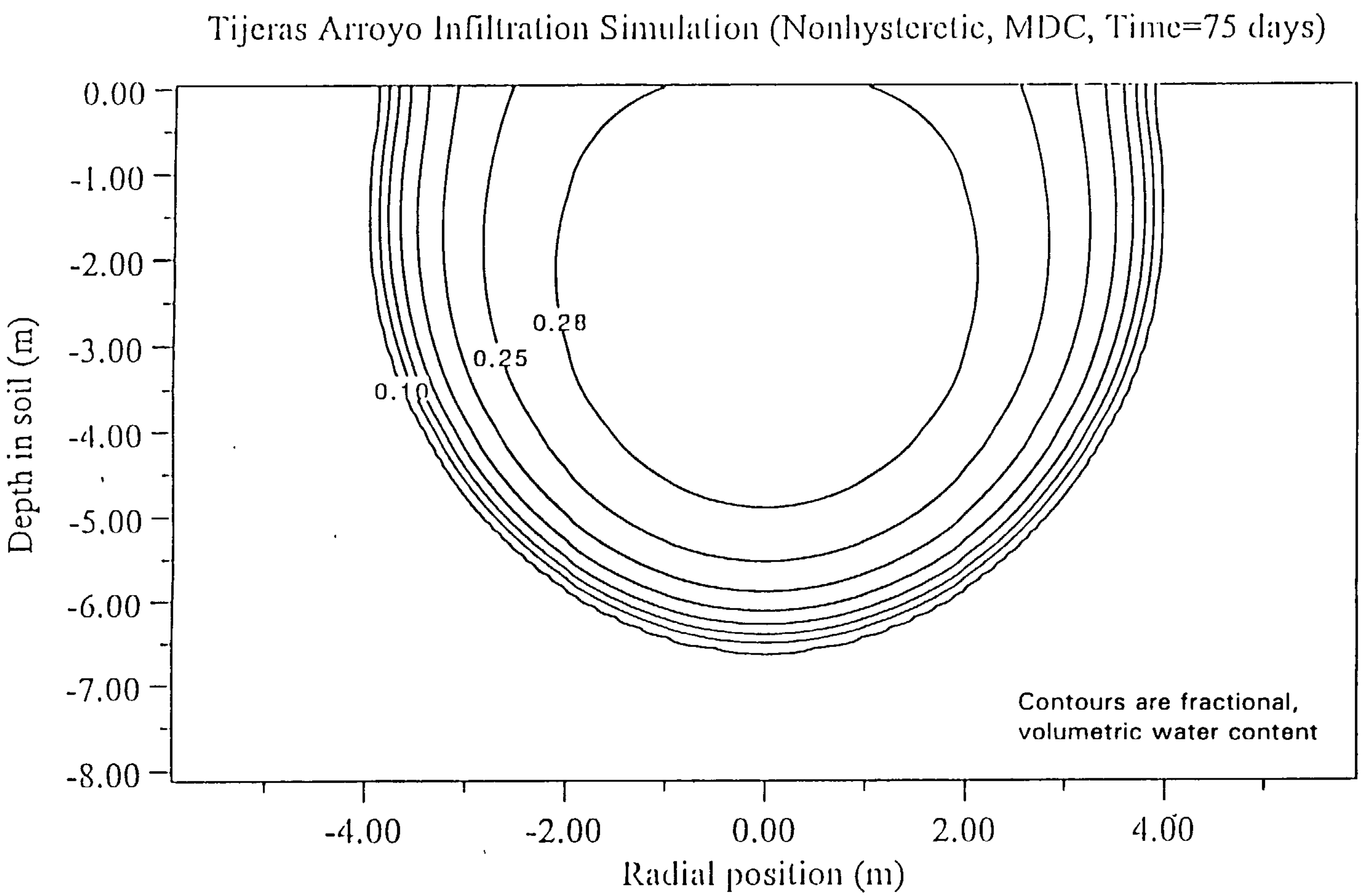


Figure 7.9: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MDC, Time = 75 days)

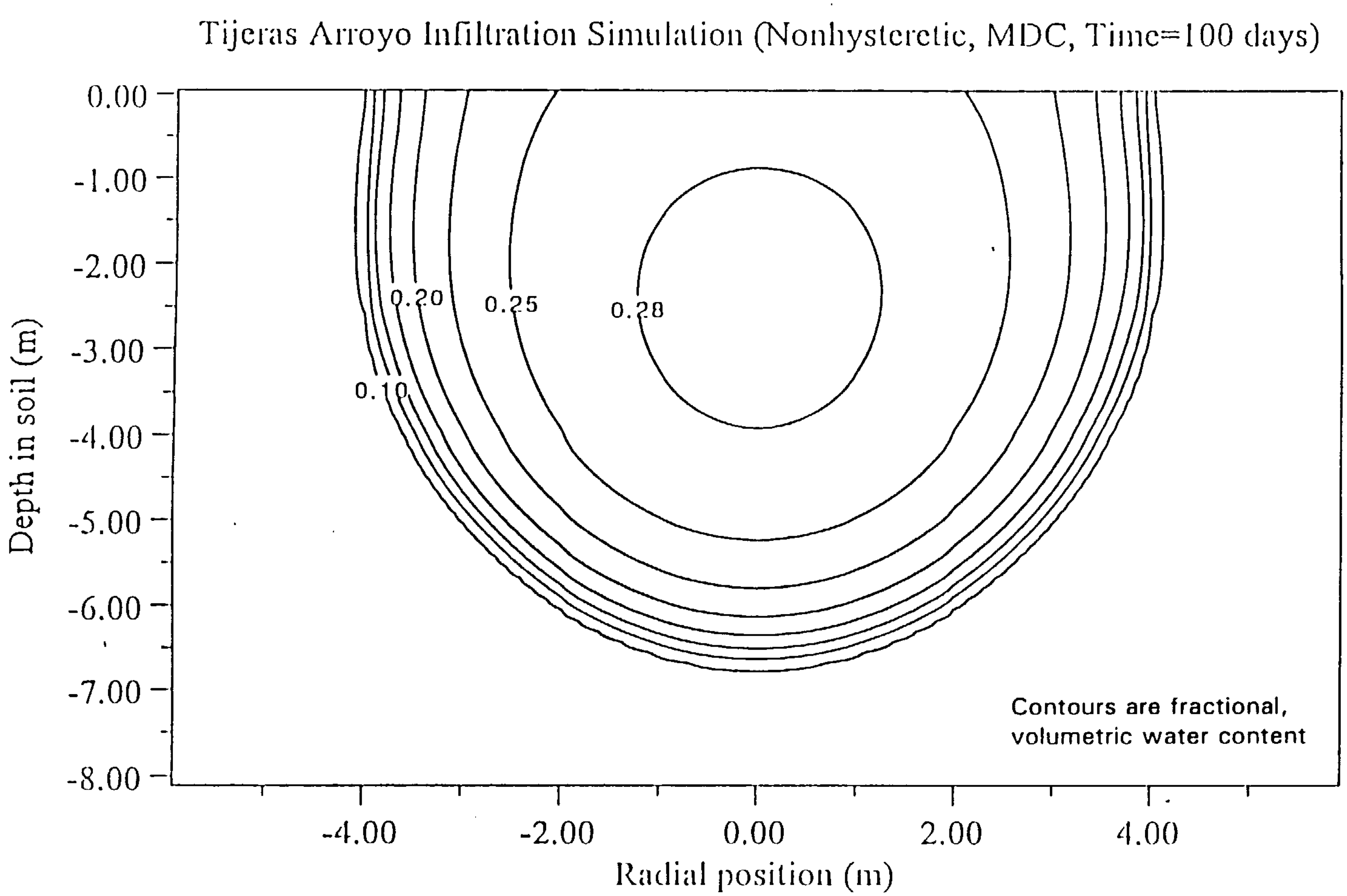


Figure 7.10: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MDC, Time = 100 days)

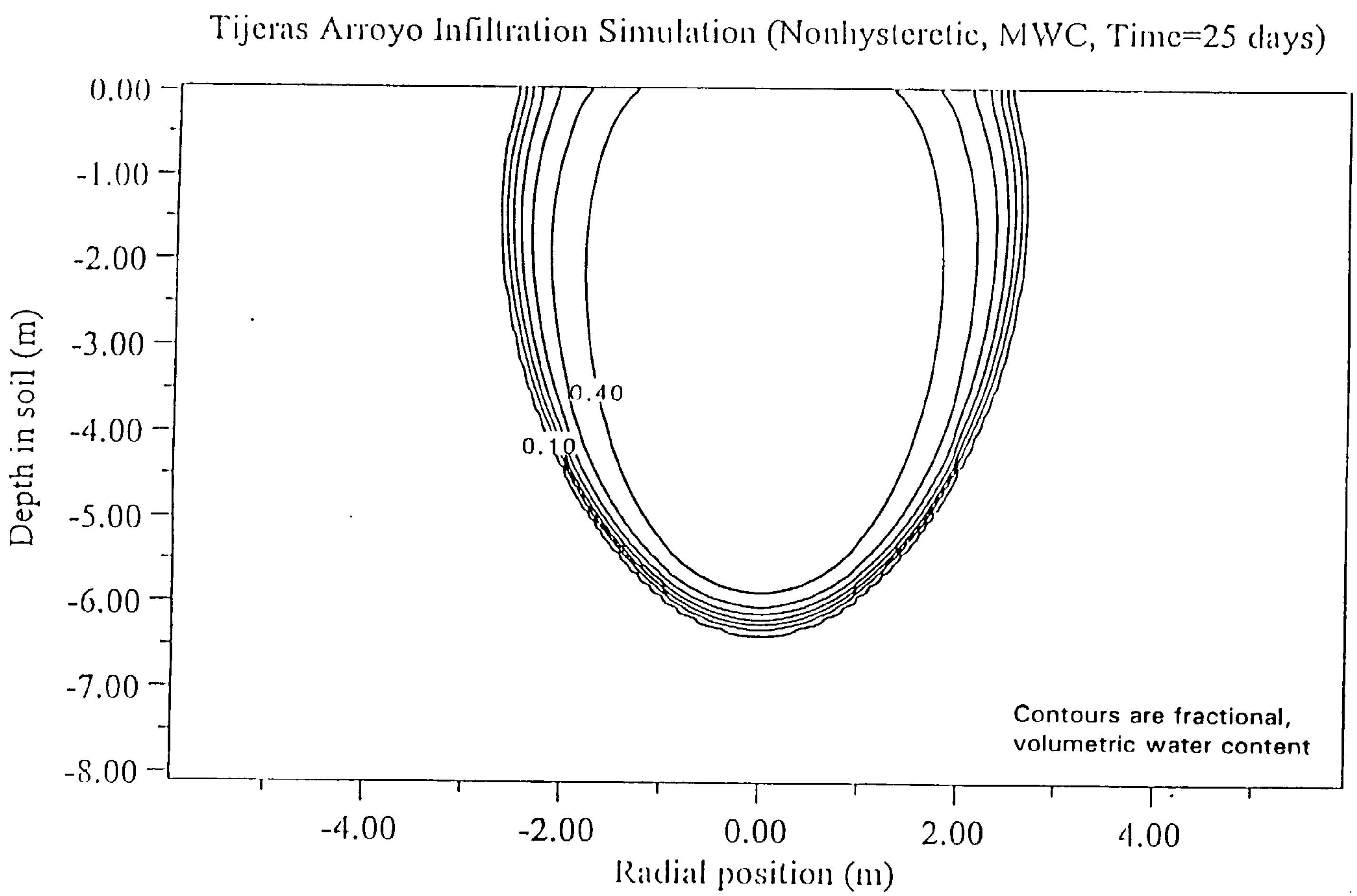


Figure 7.12: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MWC, Time = 25 days)

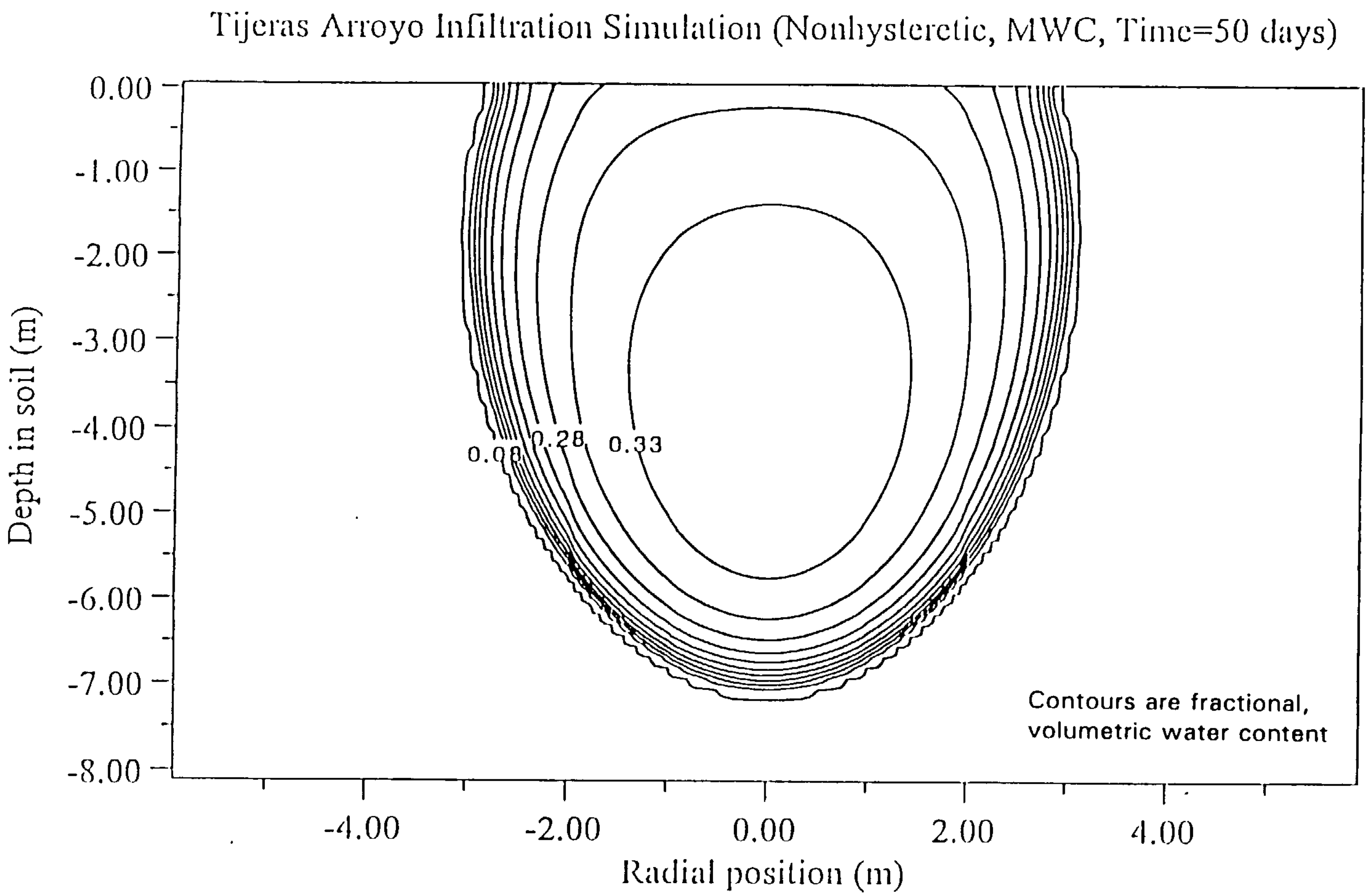


Figure 7.13: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MWC, Time = 50 days)

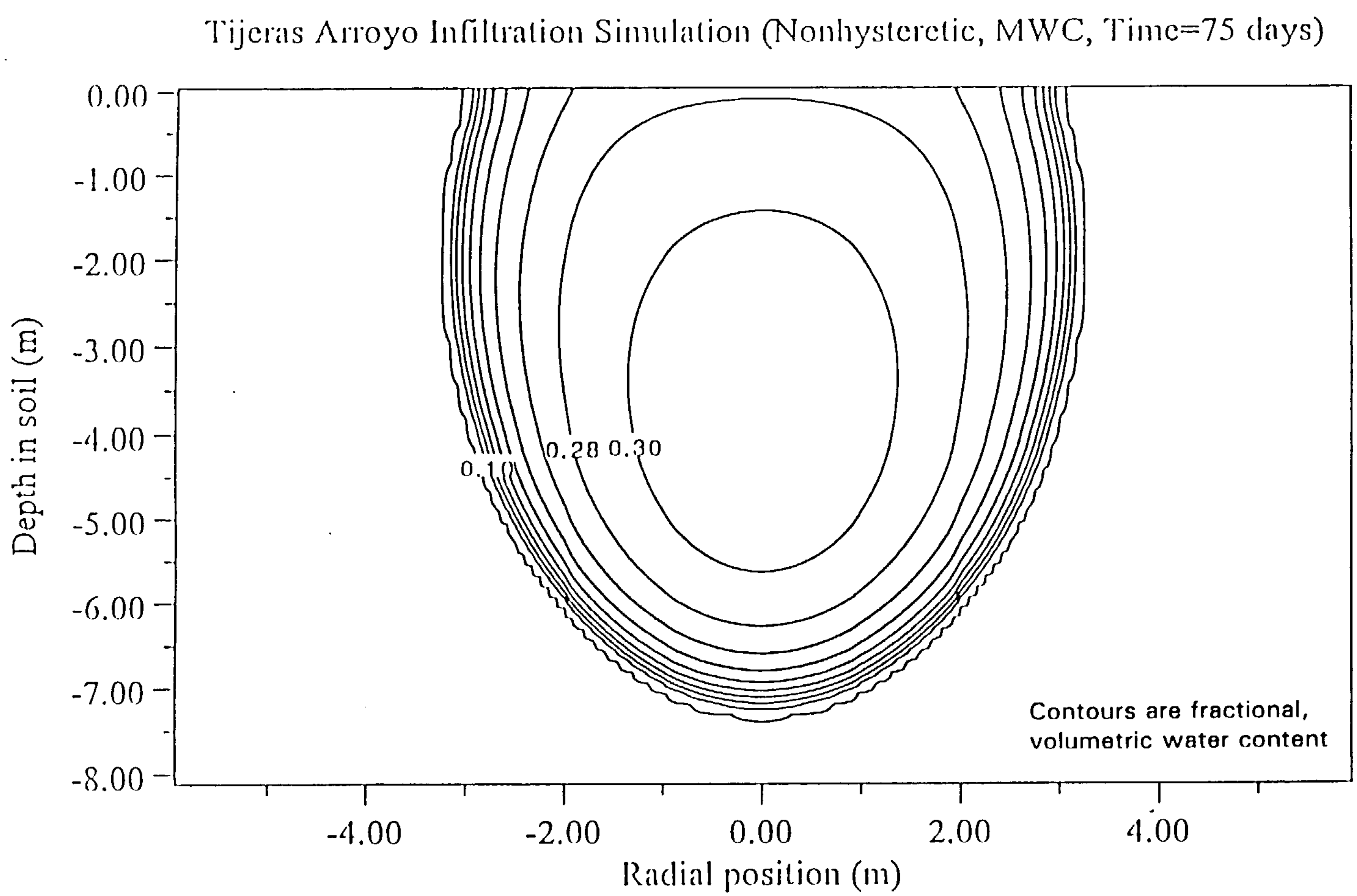


Figure 7.14: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MWC, Time = 75 days)

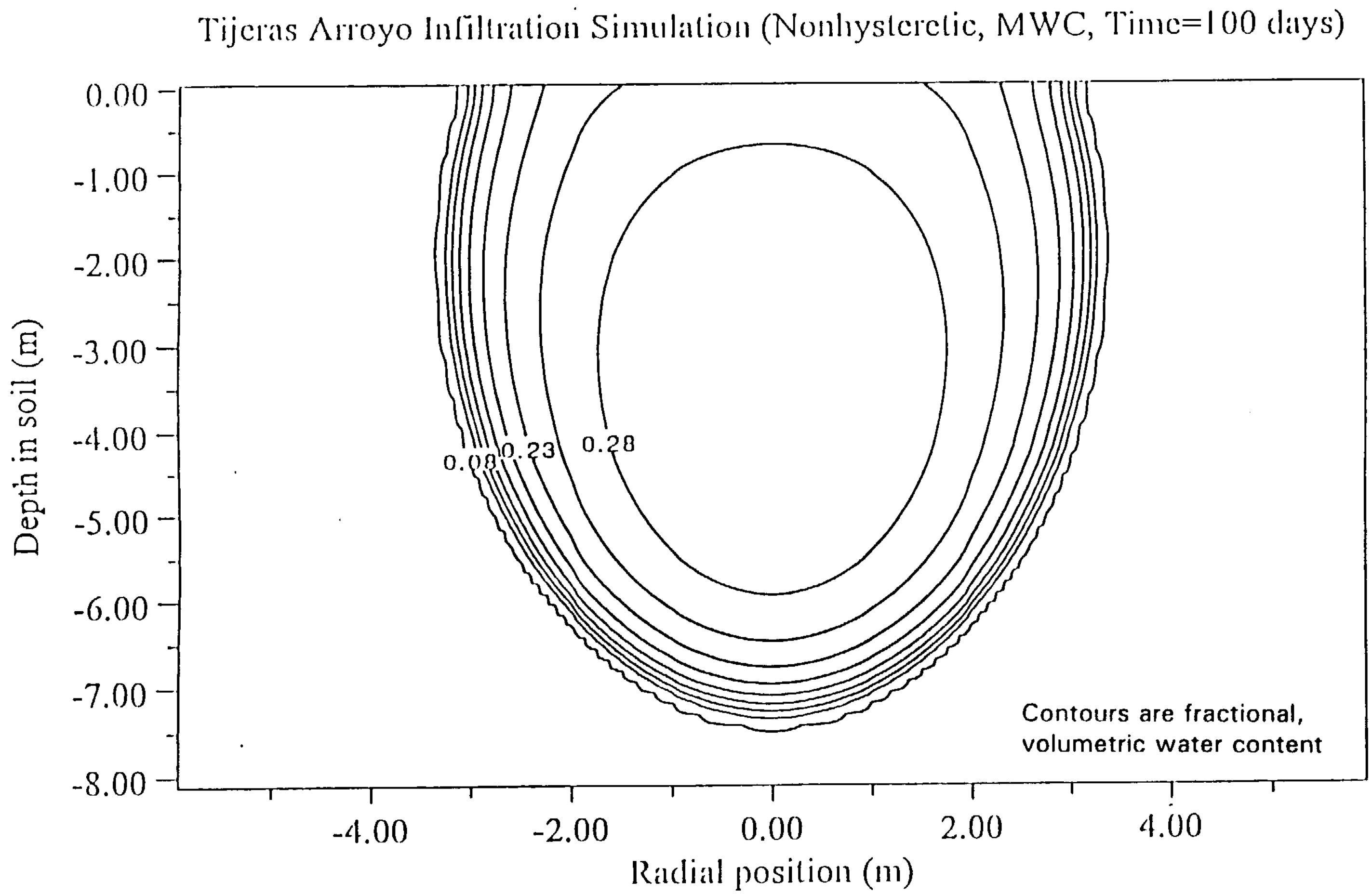


Figure 7.15: Tijeras Arroyo Infiltration Simulation (Nonhysteretic, MWC, Time = 100 days)

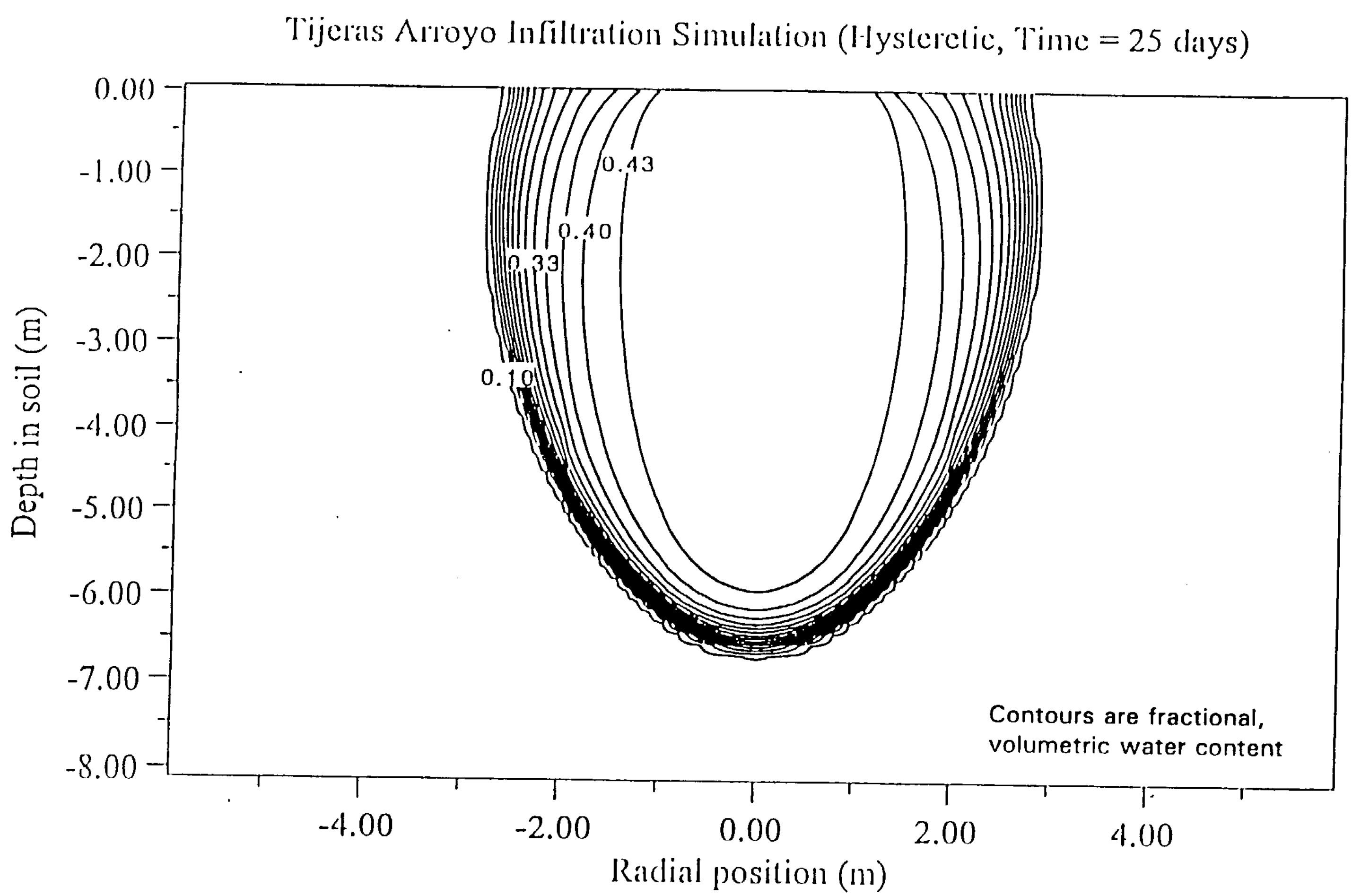


Figure 7.17: Tijeras Arroyo Infiltration Simulation (Hysteretic, Time = 25 days)

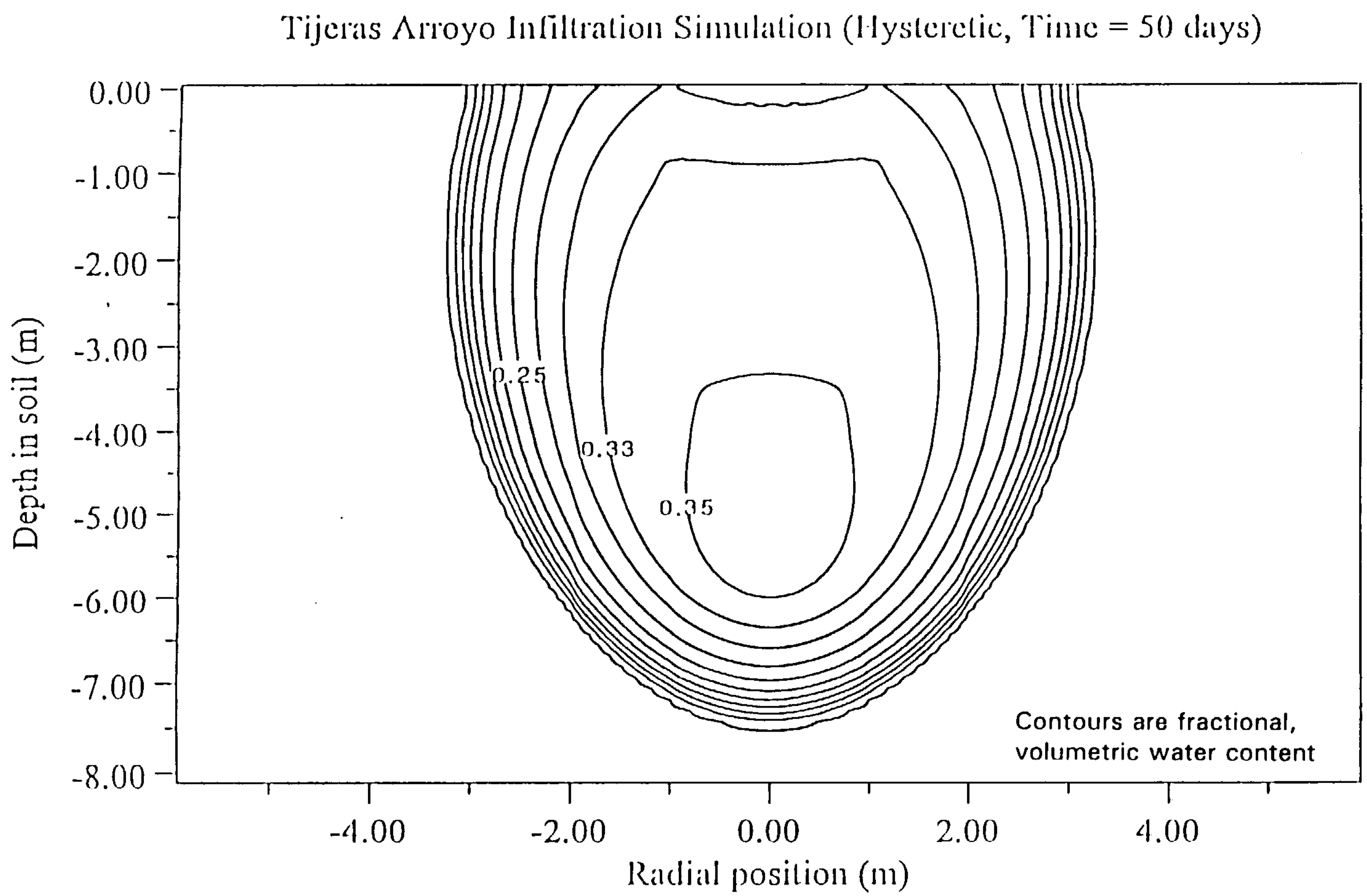


Figure 7.18: Tijeras Arroyo Infiltration Simulation (Hysteretic, Time = 50 days)

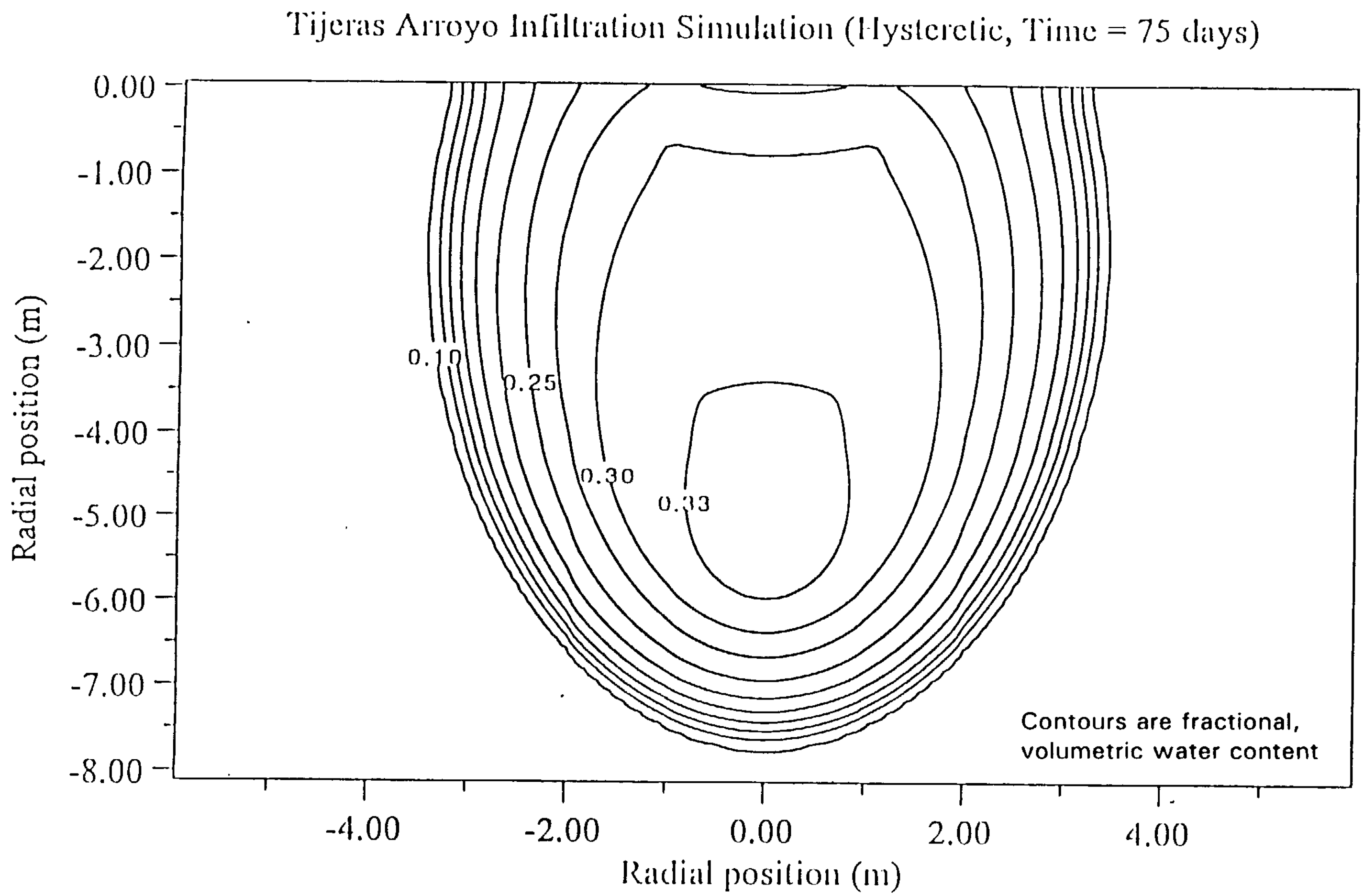


Figure 7.19: Tijeras Arroyo Infiltration Simulation (Hysteretic, Time = 75 days)

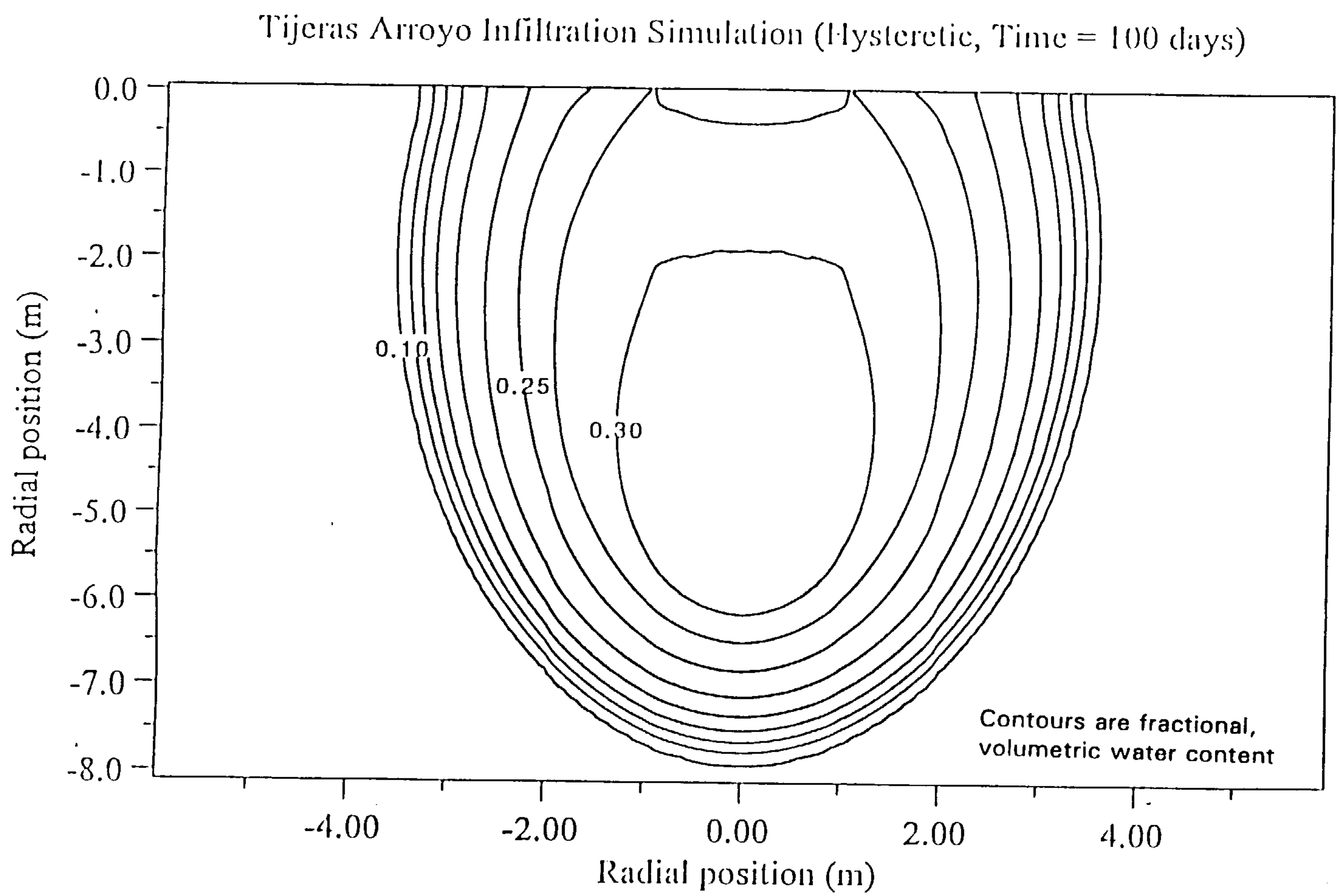


Figure 7.20: Tijeras Arroyo Infiltration Simulation (Hysteretic, Time = 100 days)

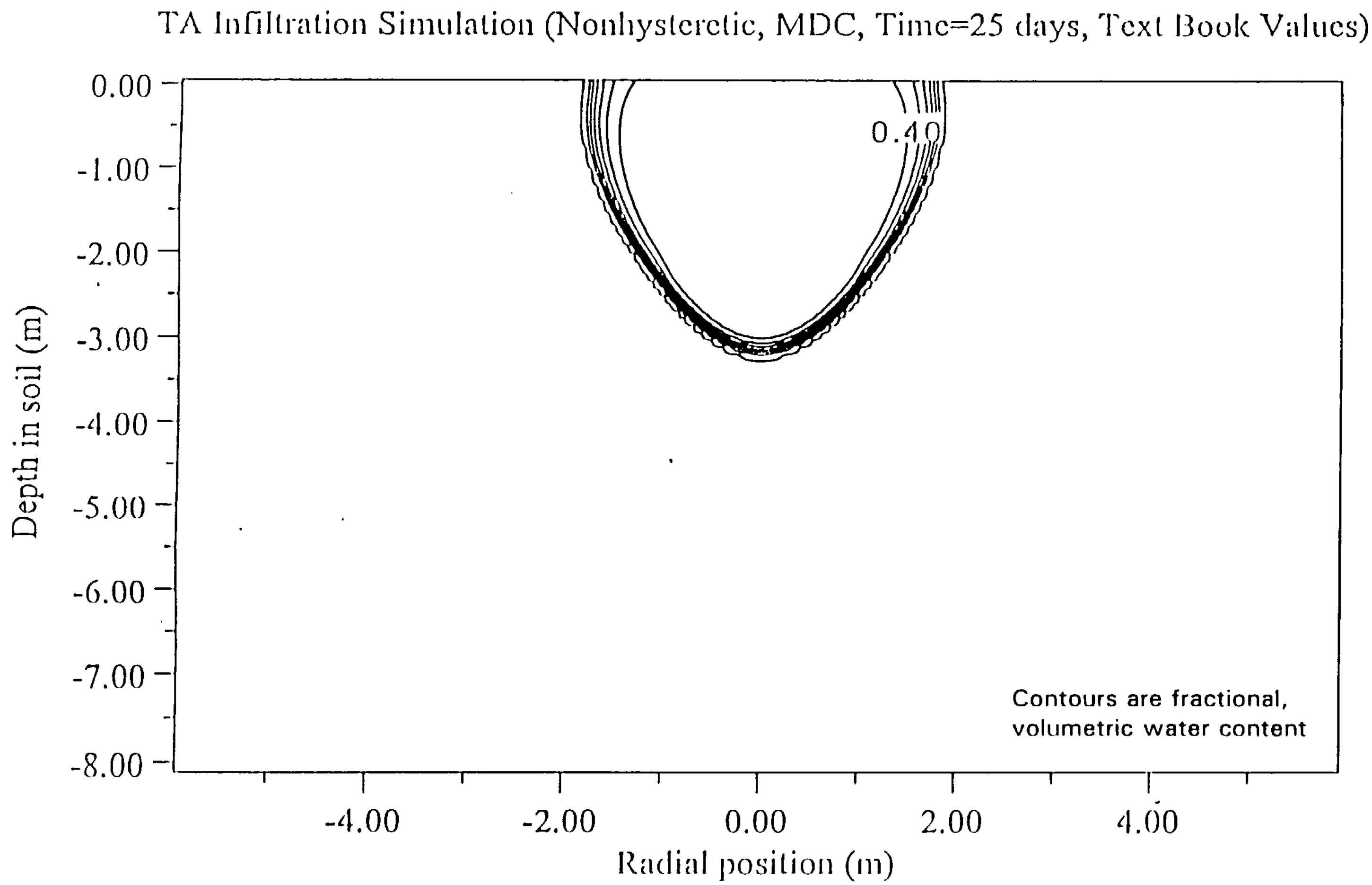
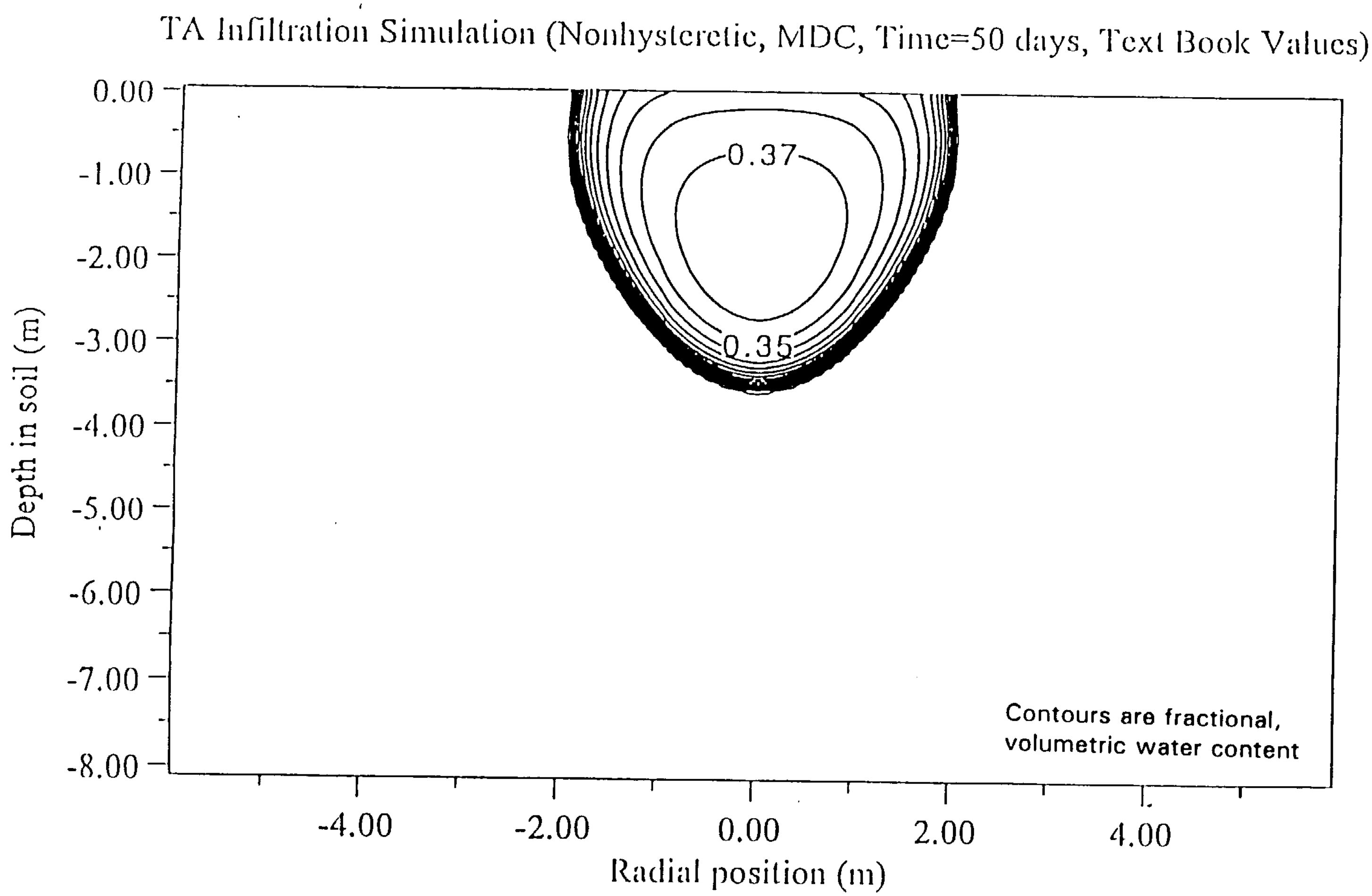


Figure 7.22: TA Infiltration Simulation (Nonhysteretic, MDC, Time = 25 days, Text Book Values)



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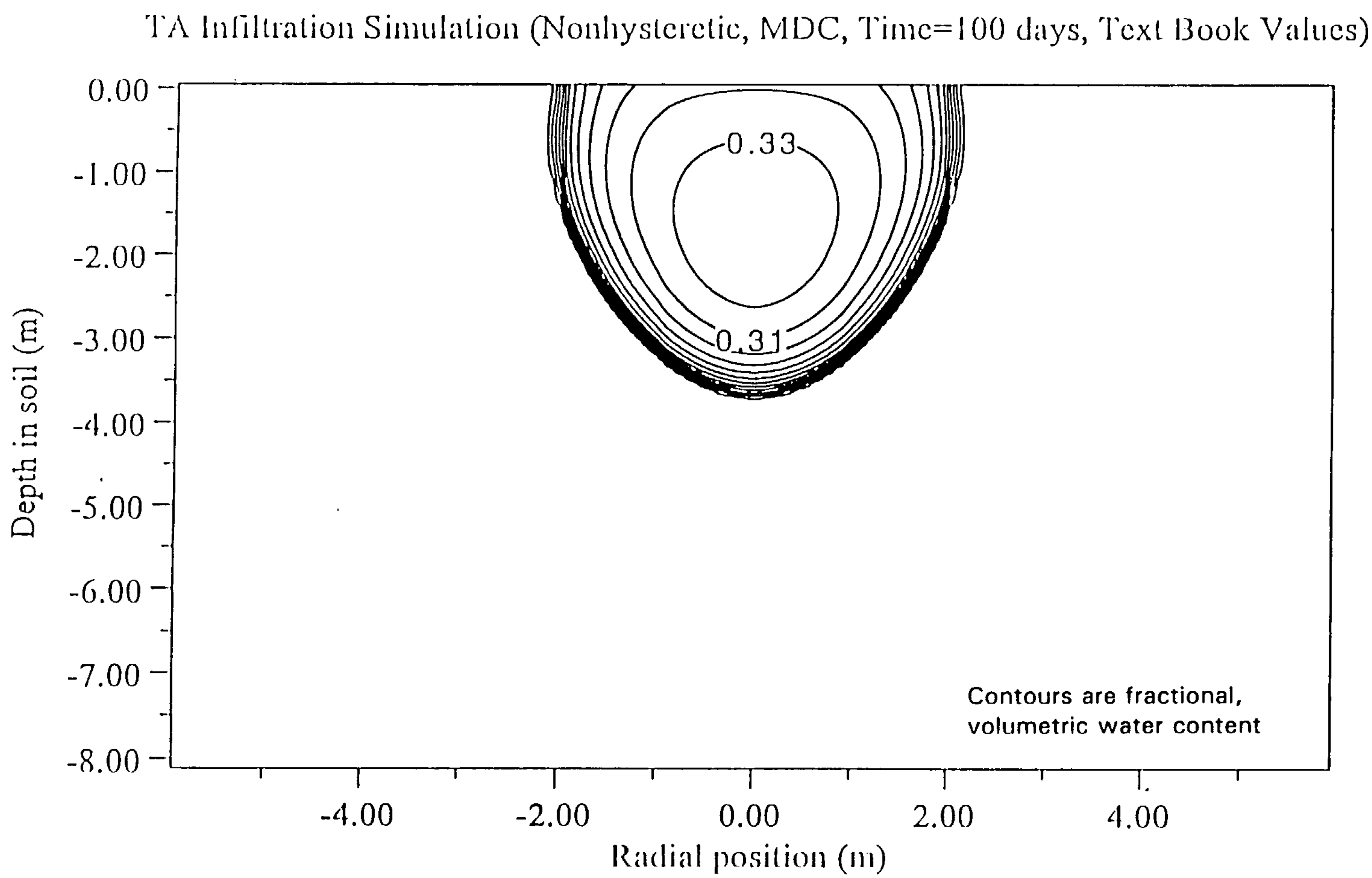

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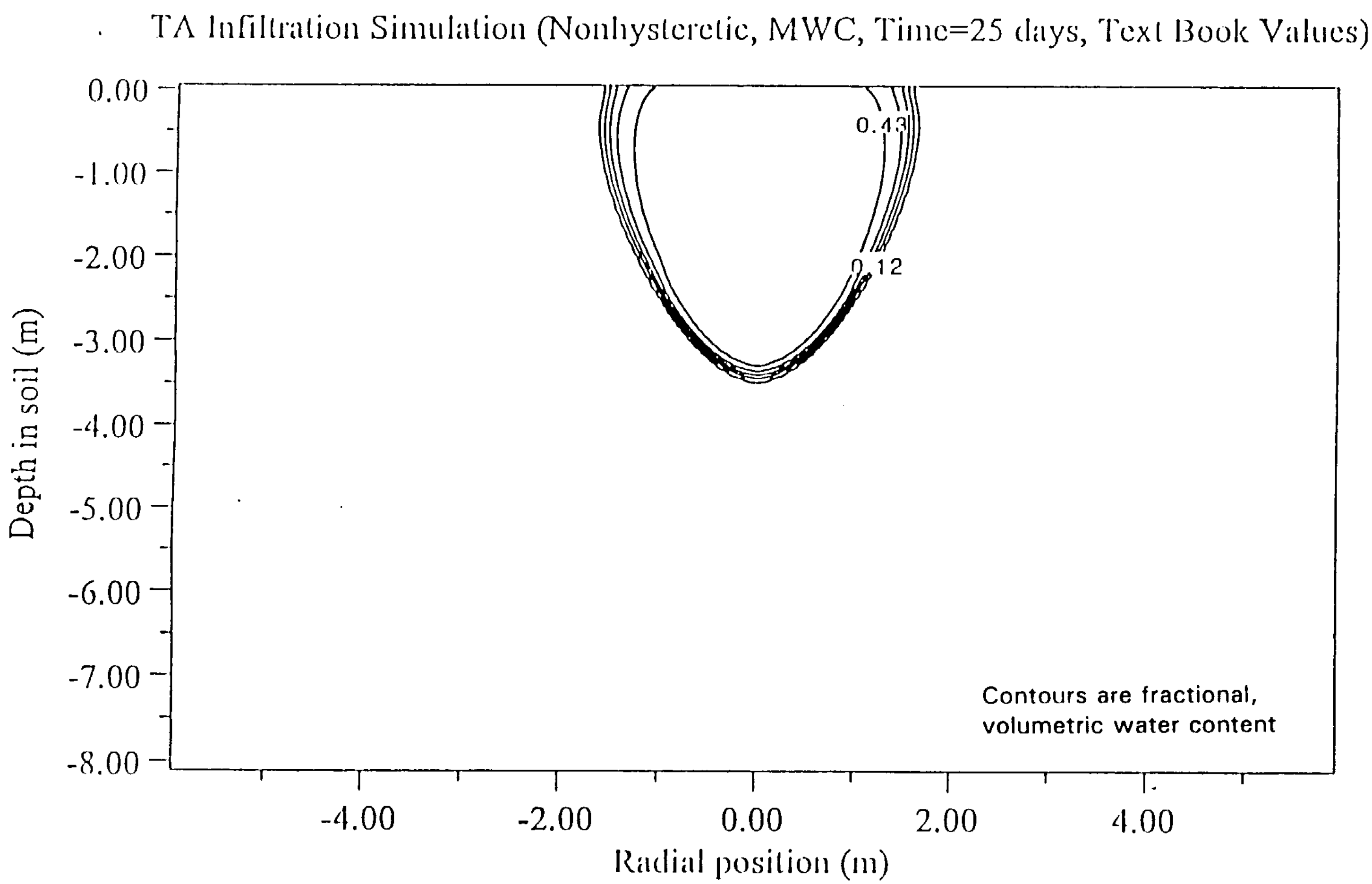

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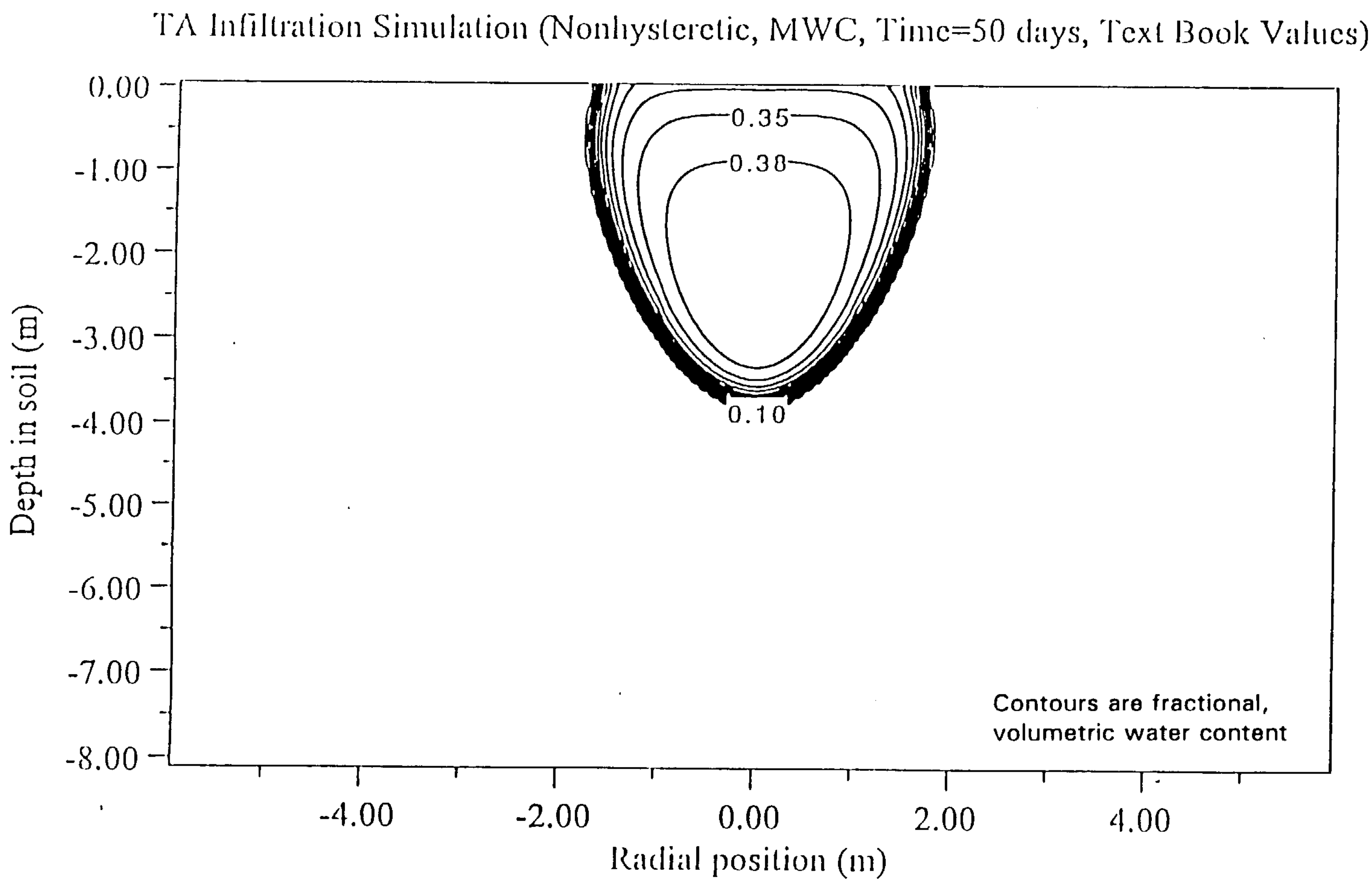

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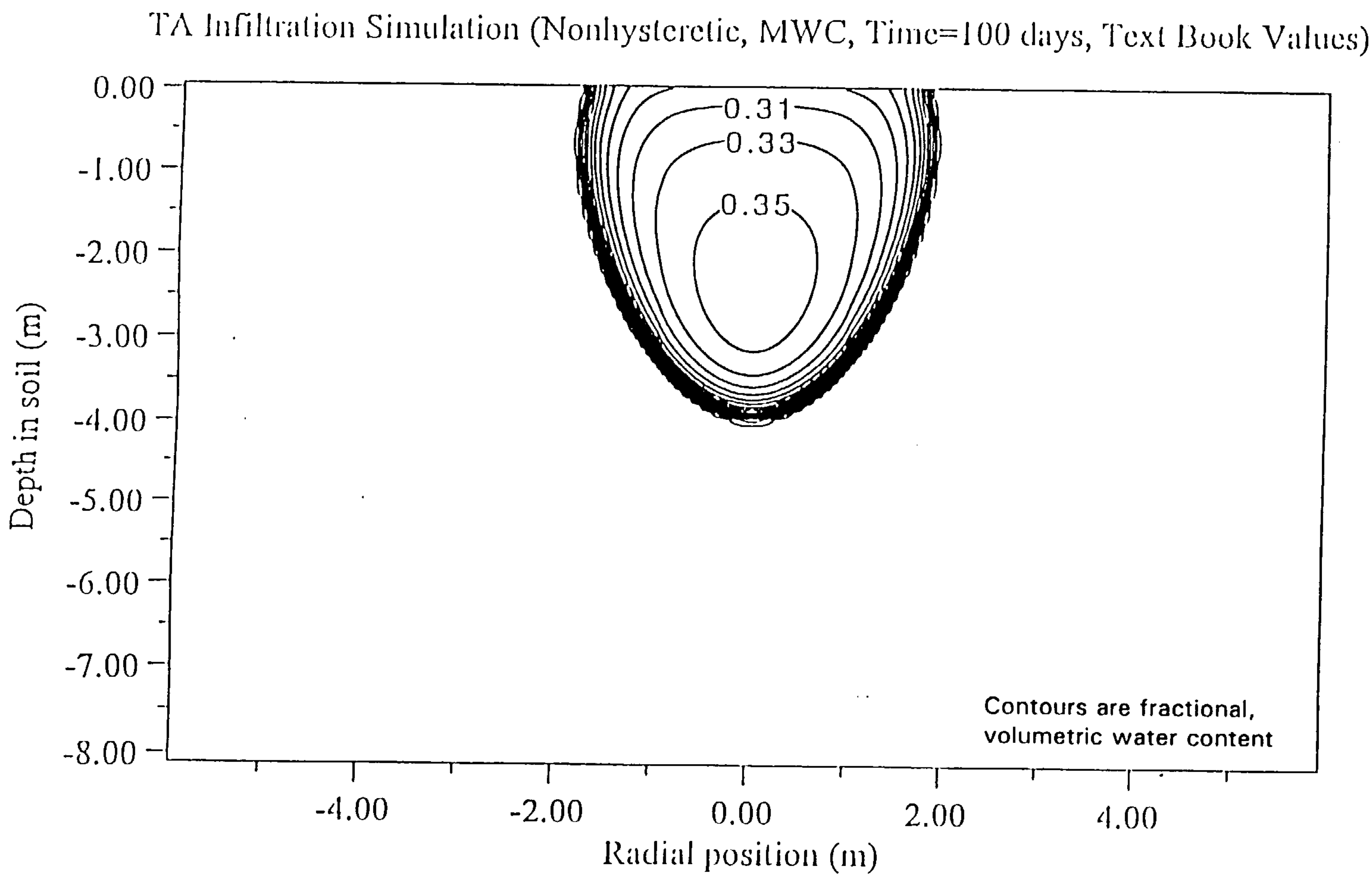

Figure 7.27: TA Infiltration Simulation (Nonhysteretic, MWC, Time = 100 days, Text Book Values)

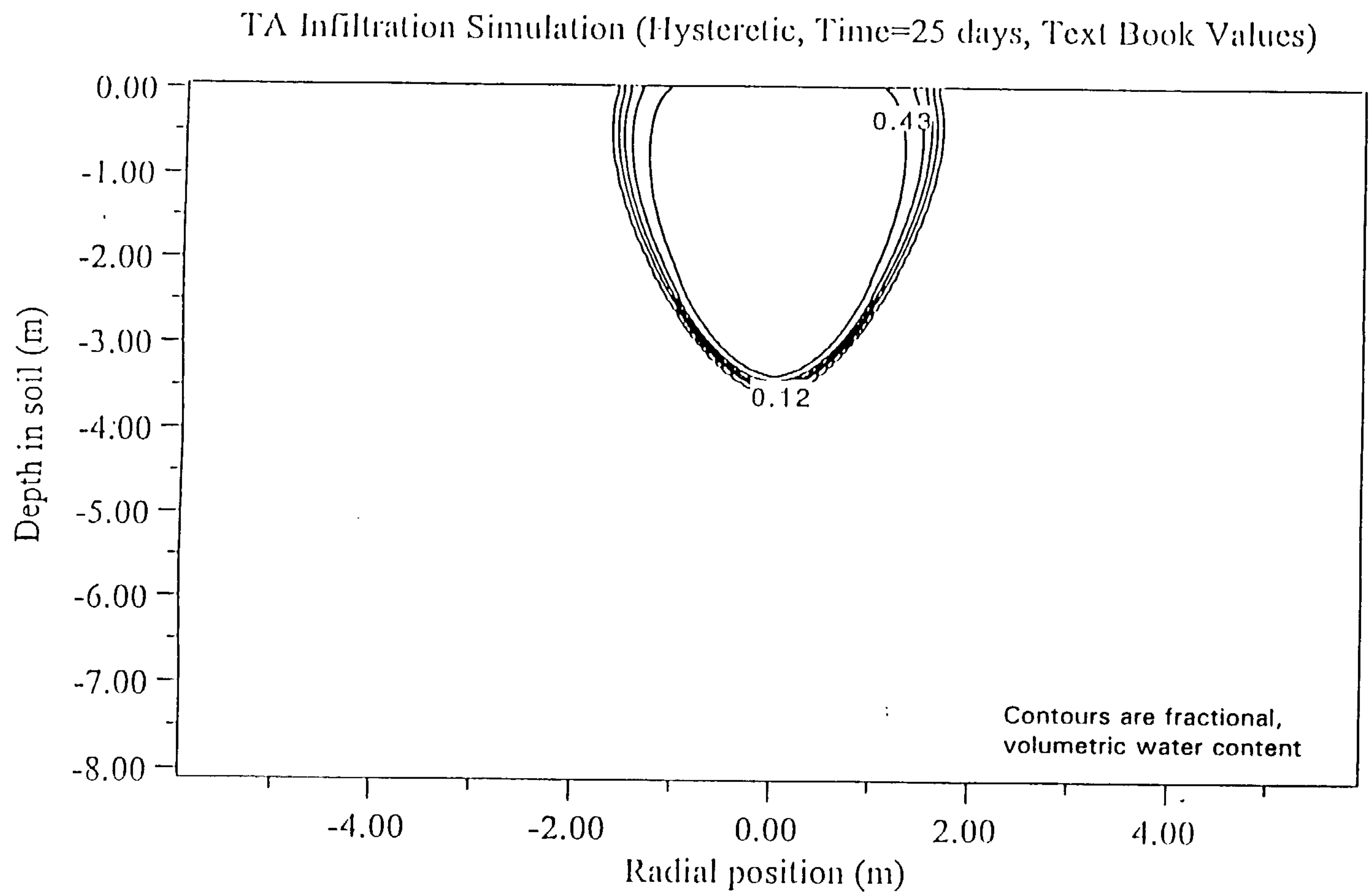

Figure 7.28: TA Infiltration Simulation (Hysteretic, Time = 25 days, Text Book Values)

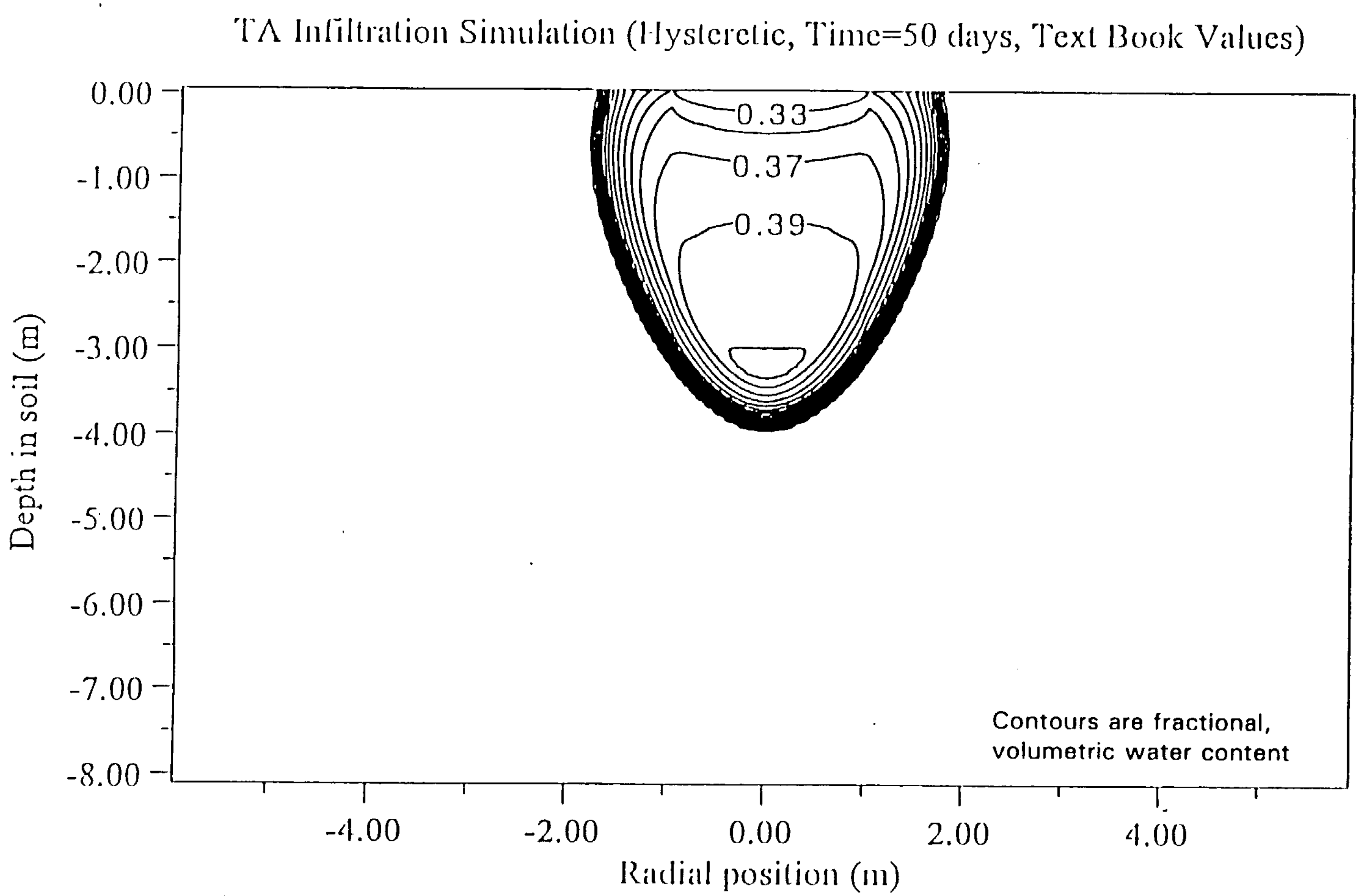

Figure 7.29: TA Infiltration Simulation (Hysteretic, Time = 50 days, Text Book Values)

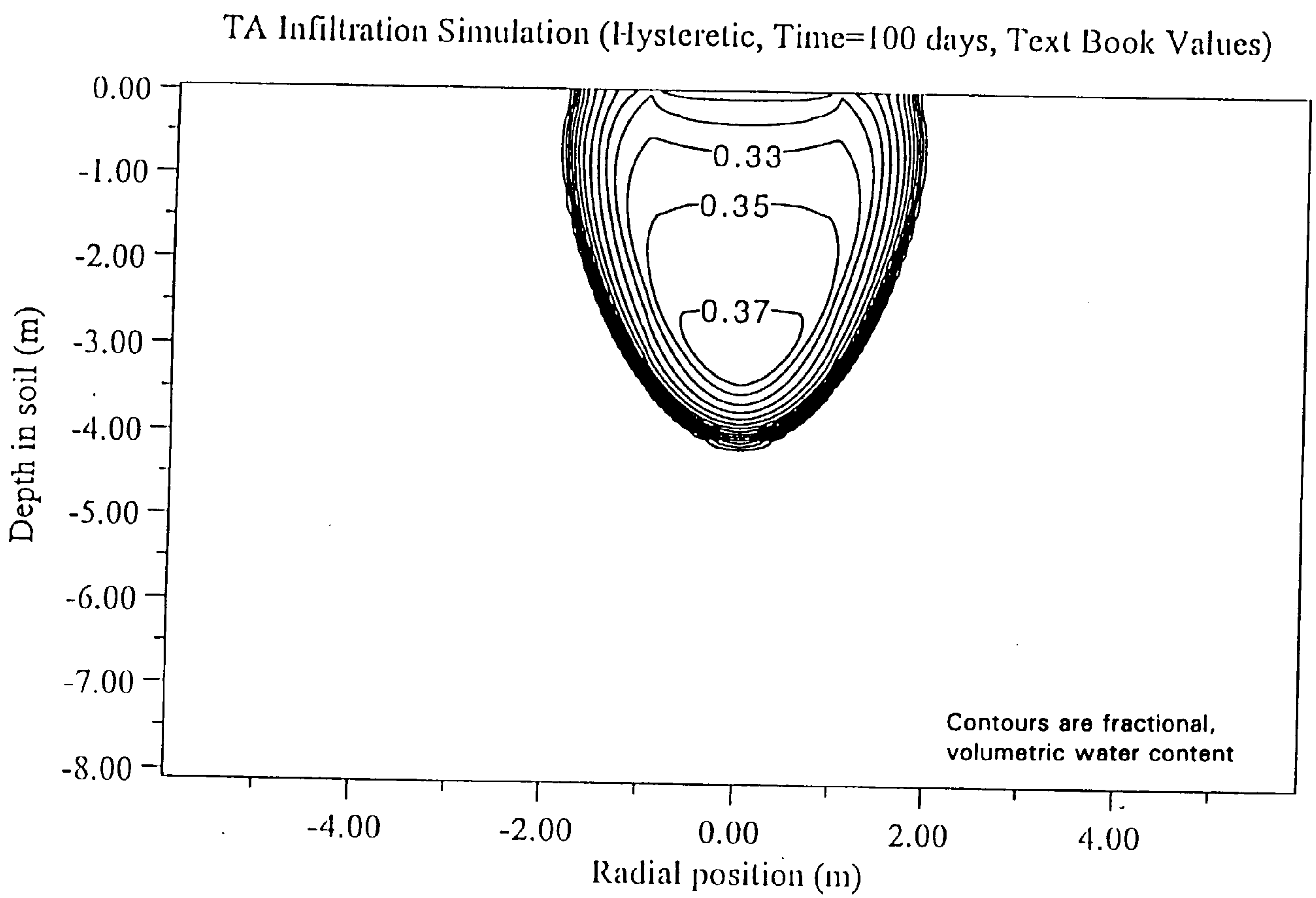

Figure 7.30: TA Infiltration Simulation (Hysteretic, Time = 100 days, Text Book Values)

Sandia National Laboratories

EVALUATION OF GROUNDWATER FLOW AND HYDROGEOLOGIC CONCEPTUAL MODEL KIRTLAND AIR FORCE BASE ALBUQUERQUE, NEW MEXICO

NOVEMBER 1997
(Revised August 1998)

Environmental Restoration Project

United States Department of Energy
Albuquerque Operations Office

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EXECUTIVE SUMMARY

A deterministic, numerical groundwater flow model of the Kirtland Air Force Base (KAFB) area was used to explore and test quantitatively the conceptual model of the hydrogeology developed by the Sandia National Laboratories (SNL) Site-Wide Hydrogeologic Characterization Project (SWHC). Information from the U.S. Geological Survey (USGS), the New Mexico Bureau of Mines and Mineral Resources, other public sources, and the SNL SWHC Project was used to develop the conceptual model of the hydrogeology in the vicinity of the site. The SNL/KAFB model builds upon the work presented in the SWHC 1993, 1994, and 1995 annual reports (SNL/NM 1994, 1995, 1996) and is consistent with the U.S. Environmental Protection Agency modeling recommendations noted in their review of the 1994 SWHC annual report. The conceptual model separated the sediments into alluvial fan and ancestral Rio Grande fluvial deposits, arranged in complex intergradational architectures. Pumping test results, water level measurements, and geological mapping from the SWHC were used to determine the distribution of facies and their hydraulic properties in the model.

The computer code MODFLOW, written by the USGS, was used to simulate the three-dimensional flow of groundwater beneath KAFB. MODFLOW is the most widely used groundwater flow model in the world and has been successfully used in analyses performed in the area by the U.S. Geological Survey and others to construct and calibrate both steady-state and transient models. The Albuquerque Basin Model (ABM), constructed by the USGS (Kernodle et al., 1995), was used as the starting point for the KAFB model. Groundwater levels have been declining since the 1960's in the KAFB area, and it was necessary to consider large-scale trends in water levels, which the ABM does. The SNL/KAFB portion of the basin model was removed by using a modified telescopic mesh refinement approach in which the flows across the boundaries and the aquifer properties were used to create a smaller, more expeditious model. The submodel grid remained the same as the ABM grid.

The fit of the USGS model to the SNL/KAFB potentiometric data was fair to poor and did not adequately replicate the major features observed in the area. Incorporating geologic data collected during the SWHC Project largely resolved these discrepancies. The model was calibrated to conditions from January 1980 to March 1995. The quantitative calibration goals that were established for this analysis were met.

The model of the SNL/KAFB domain was substantially modified over the initial configuration constructed by the USGS. Modifications made to the USGS ABM included the addition of a long, north-south strip of axial channel deposits, extending much farther than in the ABM. In addition, SWHC Project estimates of hydraulic conductivity of alluvial fan material along the mountains were much lower than in the ABM, as was recharge from infiltration along Tijeras Arroyo. In the ABM, recharge along Tijeras Arroyo is over an order of magnitude higher than that estimated by the SWHC Project, and two models were calibrated to bracket the conceptual uncertainty caused by this difference. In the first, the recharge rate specified by the USGS was maintained and the model modified to reflect the SNL/KAFB conceptual model. For the second model, recharge along Tijeras Arroyo was reduced to the value estimated by the SWHC Project. The high recharge case required high hydraulic conductivities in the alluvial fan material where Tijeras Arroyo enters SNL/KAFB. The values were not unreasonable when compared with SWHC data from Technical Area 2, but the model still exhibited a pronounced overprediction (too much water) in the area, which suggested that the Tijeras Arroyo flow rate in the ABM may be too high. In the low recharge case, hydraulic conductivities in the area where Tijeras Arroyo enters SNL/KAFB were very low.

Advective particle tracking, which represents the motion of a parcel of water, was done to estimate ultimate discharge points and associated travel times of groundwater in the SNL/KAFB area.

Sensitivity coefficient and Monte Carlo approaches were used to assess the sensitivity of the model to parameters which represent facets of the SWHC conceptual model. This allows the assessment of the adequacy of the conceptual model and determination of the most important features, which can be used to guide any further detailed investigation. The most sensitive parameters included initial heads, specific yield, specific storage, alluvial hydraulic conductivity, axial channel deposit hydraulic conductivity, and alluvial fan leakance.

Of the hydraulic parameters in the model, specific yield was most sensitive. This is consistent with the conceptual model, which holds that a large portion of the water pumped from the basin is derived from storage, and more water is released from storage per unit decline of the potentiometric surface under water table than confined conditions. Specific yield is not well characterized on SNL/KAFB or in the basin in general, which can result in compensating errors with respect to transmissivity and water budget (i.e., an error in the water budget can be compensated for by changes in hydraulic parameters).

The sensitivity of the model to two relatively poorly known parameters, initial head and specific yield, has a deleterious effect on the predictive capability of any model of the basin because it is possible to have compensating errors in parameter values. In the case of initial heads, it is simply not possible to overcome the data deficiency from earlier in this century. However, the purpose of this analysis was comparative, and the difference in representations the important result. The numerical representation of the conceptual model developed by the SWHC Project appears to adequately represent reality.

1.0 INTRODUCTION

1.1 Background

The Sandia National Laboratories/Kirtland Air Force Base (SNL/KAFB) area encompasses 52,223 acres (ac) bounded on the north and northwest by the City of Albuquerque, New Mexico; on the east by Cibola National Forest; on the south by Isleta Pueblo; and on the west by land owned by the State of New Mexico, KAFB (buffer zones), and the Albuquerque International Airport. SNL occupies 2,820 ac within KAFB and consists of five main work areas, called technical areas, and additional test areas, such as Thunder Range south of Technical Area III (TA-III) and Coyote Canyon Test Field in the canyons on the east side of the Manzano Mountains (also called the Manzano Base). See Figure 1.1 for the location map.

1.2 Project Objectives

In order to have a successful modeling project, it is crucial that the project objectives be defined before the project starts. The overall goal of this project was to construct a model to be used to assess the Site-Wide Hydrogeologic Characterization (SWHC) Project conceptual model and develop a quantitative understanding of groundwater flow paths in the SNL/KAFB area. The modeling analysis also includes discussions of potential limitations of the model and an assessment of its accuracy.

1.3 Previous Groundwater Modeling Analyses

Two large regional-scale analyses have been conducted for the Albuquerque Basin (Kernodle and Scott, 1986; Kernodle et al., 1987; Kernodle et al., 1995) and will be reviewed briefly. Site-specific models have also been developed (e.g. for the Chemical Waste Landfill [CWL]) that will not be discussed here because they do not attempt to provide a site-wide interpretive perspective. Kernodle and Scott (1986) developed a three-dimensional model of steady-state flow in the Albuquerque Basin. Kernodle et al. (1987) present the extension of Kernodle and Scott's model to simulation of transient groundwater flow in the Albuquerque Basin. Both the previous models used the conceptual model developed in the 1960's, which had the highly productive aquifer (Santa Fe Group sediments) being much thicker and extensive than recent data has revealed. These (1986 and 1987) models do not adequately represent the current understanding of the Albuquerque Basin and will not be discussed further.

Rapid water level declines in the late 1980's and early 1990's suggested that the early conceptual model of the Albuquerque Basin was incorrect, and a series of investigations was undertaken to better define the hydrogeology of the basin. The results of the first phase, development of a detailed geologic framework, are summarized in Hawley and Haase (1992). This investigation revealed that the productive part of the Santa Fe Group was primarily associated with axial channel deposits of the ancestral Rio Grande. Thorn et al. (1993) performed a detailed assessment of hydrologic conditions as the second phase of the assessment, and Kernodle et al. (1995) translated the conceptual model developed by Hawley and Haase and Thorn et al. into a numerical model of the Albuquerque Basin to be used for water resource management. A more detailed discussion of the portion of the U.S. Geological Survey (USGS) model that covers the SNL/KAFB area is provided in section 4.2.1.

A two-dimensional, steady-state MODFLOW model was used to perform a reconnaissance of possible conceptual models for the SNL/KAFB area (SWHC 1995). An inverse technique was used to estimate model parameters. The results suggested that recharge was higher underneath arroyos, transmissivity is lower on the east than transmissivity to the west. The change from lower to higher hydraulic conductivity from east to west is generally consistent with the depositional model, which has alluvial fan deposits near the mountain front and axial channel deposits to the west. The use of a two-dimensional and steady-state approach was a simplification that limited the further extension of the model. Consequently, the groundwater flow model constructed in this analysis was transient (time-varying), and was derived from the model of Kernodle et al. (1995).

1.4 Report Organization

This report is organized into six chapters; tables will appear at the end of individual chapters, and all figures will appear at the end of the report. Chapter 1, the introduction to the report, summarizes the analysis and puts the work into perspective relative to past groundwater modeling analyses done in the area.

Chapter 2 discusses the hydrogeologic framework upon which a conceptual model of groundwater flow and transport in the area is based. Local and regional geology, hydrology, and groundwater flow are discussed in this chapter.

Chapter 3 presents the computer code selected for the analysis and how the model was constructed. Representation of the Rio Grande, pumping wells and recharge, and the general implementation of the conceptual model in the computer program is also described.

Chapter 4 describes the calibration methodology, procedures, and results. Final model parameterization is also presented. Chapter 5 discusses the analysis results and presents its conclusions, and Chapter 6 presents the references.

2.0 CONCEPTUAL MODEL

A conceptual model is a concise description of the components of the groundwater flow system and is developed from regional, local, and site-specific data. A conceptual model is a precursor to the development of a mathematical model and identifies groundwater sources and sinks, geologic origin and configuration of the aquifers, aquifer properties, and general flow system behavior. The conceptual model guides the construction and calibration of the numerical model and aids in interpretation of model results by presenting a general understanding of the groundwater flow system.

2.1 Regional Hydrogeology

The Albuquerque Basin is located in the Rio Grande Valley (Figure 2.1). Low topographic relief characterizes the floor of the basin (elevation 4,900 ft msl), the Sandia and Manzano Mountains (elevation 10,000 ft) are the eastern basin boundary, and a gentle rise to the plains forms the western boundary (elevation 6,500 ft). The Albuquerque Basin has no distinct north and south boundaries; rather, the northern limit is generally established where the Sandia and Jemez Mountains created a narrowing of the alluvial deposits. Over the last 30 million years, the deep valley has been filled in by erosion of the mountains around the basin and by sediment brought into the basin and deposited by rivers. These deposits are comprised, in part, of the late Oligocene to middle Pleistocene Age Santa Fe Group sediments, which range in thickness from 2,400 to 13,800 ft in the Albuquerque area (Hawley and Haase, 1992). The Santa Fe Group (SFG) is subdivided into Lower, Middle, and Upper units (Hawley and Haase, 1992). The Upper Santa Fe Group (USF) is the formation used almost exclusively for groundwater supply in the Albuquerque Basin.

During the time that the lower part of SFG was deposited, the basin was closed, and sediments that collected were fine grained from the then still low relief rift margins and playa-lake evaporitic deposits. Rifting accelerated during the deposition of the middle and upper SFG, and a through-flowing drainage system developed from the north (Thorn et al. 1993). Either the energy of the fluvial system was lower during deposition of the middle part of the SFG, or there was an influx of fine sediments into the active rift, since the middle SFG sediments are generally finer and less permeable than those of the upper part of the SFG. An ancestral river system was guided to the eastern side of the rift by rapid subsidence of the eastern part of the area during the time of the deposition of the middle and upper SFG. During deposition of the upper SFG, the fluvial depositional environment for axial channel deposits was especially energetic, and the deposits were coarse and well sorted. The position of the interface between the fluvial deposits (laid down in a north-south direction) and the alluvial fan sediments (directed east-west) remained sharp and stable for millions of years. Thorn et al. (1993) and Ruskauff (1996) both show mappings of the hydraulic conductivity of the USF.

The USF is characterized by intertonguing piedmont-slope alluvial fan and fluvial basin-floor deposits. Piedmont-slope deposits consist of poorly sorted, weakly stratified sand and conglomerate with a silt-clay matrix. Basin-floor deposits include cross-stratified ancestral river sediments characterized by thick zones of clean sand and gravel. Fine- to medium-grained overbank sediments were deposited in areas where major river systems were merging and in basin-flow and piedmont-slope transition zones. The thickness of the USF can be as much as 400 m, but is usually less than 300 m. Three hydrostratigraphic units are distinguished within the USF, including a coarse-grained alluvial fan pediment veneer facies in the eastern part of the basin, fluvial deposits of the ancestral Rio Grande, and alluvial and minor eolian deposits in the western part of the basin (Hawley and Haase, 1992). A generalized stratigraphic column is shown in Figure 2.2, and the general conceptual arrangement of facies is shown in Figure 2.3.

Barriers and preferential groundwater flow paths both exist within the SFG. Barriers include pinch out of productive material, for instance, as channel deposits grade and abut into distal alluvial deposits. The width of the most productive aquifer material, the axial channel deposits, is from about 2 to 6 miles. Faults are also barriers to groundwater flow within the basin. Faulting within the basin can juxtapose productive aquifer units against unproductive units, abruptly terminating high hydraulic conductivity material and creating a barrier to groundwater flow. It is believed that cementation of faults has further restricted flow (Thorn et al. 1993). Preferential flow paths occur within the braided-stream deposits associated with channel deposits and as gravel and sand deposit within alluvial fan deposits.

The Rio Grande extends the length of the Albuquerque Basin and is the only perennial stream in the basin. Water is diverted from the Rio Grande into a series of canals for irrigation of land in the inner valley. Drains, which intercept groundwater and receive return flow from canals, return water to the Rio Grande. Groundwater is the primary source of water for urban, rural, commercial, and industrial uses in the Albuquerque Basin. Groundwater in the Albuquerque Basin comes from three sources: depletion of aquifer storage, capture of mountain-front and tributary recharge, and induced recharge from the Rio Grande surface-water system. The effects of faults as barriers to flow was noted by Thorn et al. (1993).

The Albuquerque Basin has been extensively studied, and the reader is referred to Theis (1938), Theis and Taylor (1939), Bjorkland and Maxwell (1961), Reeder et al. (1967), Lambert (1968), U.S. Army Corps of Engineers (1979), Hudson (1982), Kelley (1977); Kelly (1982), Kues (1986; 1987), Anderholm and

Bullard (1987), Lozinsky (1988), Kaehler (1990), Hawley and Haase (1992), Haywood (1992), Summers (1992), Thorn et al. (1993), and Hawley and Whitworth (1996) for more detail.

2.2 Site-Specific Hydrogeology

SNL/KAFB is located along the eastern margin of the Albuquerque Basin. The fault system that forms the eastern boundary of the basin bisects the area occupied by SNL/KAFB (Figure 2.4). The north to south striking Sandia fault enters the base from the north; almost colinearly the Hubbell Springs fault extends from the south; and the Tijeras fault cuts the base diagonally from the northeast. The topography is characterized by a series of alluvial fans that extend from the base of the mountains on the east to terraces along the river (Figure 2.5). The north- to south-trending fault complex divides the local groundwater flow system into three distinct hydrogeologic regions. The region west of the fault system is identified as Hydrogeologic Region 1 (HR-1). Hydrogeologic Region 2 (HR-2) is associated with the fault system, and Hydrogeologic Region 3 (HR-3) is located east of the fault system. Figure 2.6 shows the locations of these three hydrogeologic regions. HR-1 is part of the Albuquerque Basin and is of principal concern in the modeling analysis since HR-1 contains most of the SNL sites that may have been impacted by past SNL operations. Only HR-1 will be discussed further; for information on the other regions, the reader is referred to the SWHC Project reports (SNL/NM 1994, 1995, 1996). HR-1 and HR-2 are not incorporated in this groundwater flow model.

2.2.1 Stratigraphy

The sediments in the SNL/KAFB area are derived from two depositional processes: an alluvial-fan system with sediment sources located in the mountains to the east and a through-flowing north-to-south fluvial system. From SWHC Project geologic investigations, it is possible to recognize four mappable lithofacies: (1) coarse, proximal to medial alluvial-fan dominated by gravel and coarse sand, (2) fine, medial to distal alluvial-fan dominated by fine sand, silt, and clay, (3) fine fan and eolian, and (4) ancestral Rio Grande fluvial, ranging from coarse to fine-grained units. Seven geologic cross sections show the distribution of the four lithofacies (Figure 2.7 to 2.14).

In addition to the general basin geologic conceptual model developed by Hawley and Haase (1992), an analog for the SNL/KAFB portion of the basin is provided by the depositional model of the Palomas and Northern Mesilla Basins of the southern Rio Grande rift (Mack and Seager, 1990). These basins and the SNL/KAFB portion of the Albuquerque Basin share the same asymmetry, with an upfaulted mountain range on one side, a rapidly subsiding basin adjacent to the uplift, and a basin floor rotating downward along the bounding, normal fault. Mack and Seager (1990) argue that the areal distribution of alluvial-fan vs. axial fluvial lithofacies is tectonically controlled by this asymmetry and the distribution occurs in two stages (Figure 2.15). In the synorogenic stage, subsidence greater than the ability of the sediment source to equalize results in fluvial sedimentation over the axis of maximum subsidence close to the mountain front. Coarse-grained alluvial sediment is restricted to a narrow belt at the foot of the mountains. In the postorogenic stage, the rate of subsidence slows, the sediment source delivers alluvial sediment faster than subsidence occurs, and coarse-grained alluvial fans grow basinward and displace the axial river.

The uppermost aquifer underlying HR-1 is within the USF and is an unconsolidated to partially indurated, porous-media aquifer. The USF sediments that provide the framework for this aquifer include a heterogeneous mix of coarse- to fine-grained sands, silts, and clays that exhibit a complex sedimentary framework, characterized by variability in bedding thickness, continuity, and connectivity. The complex sedimentary framework includes the intertonguing of ancestral Rio Grande fluvial facies with alluvial fan facies extending westward from the highlands to the east. The fluvial facies includes thick, well-sorted, cross-stratified sand and pebbly gravel channel deposits and fine- to medium-grained sand overbank deposits. This fluvial facies is characterized by well-developed bedding, with channel deposits generally oriented north-south. The alluvial fan facies is characterized by poorly sorted, weakly stratified sand and conglomerate with an abundant silt and clay matrix. In this facies, the bedding is less continuous with alluvial channel deposits generally oriented east-west.

2.2.2 Hydraulic Properties

The water table underlying the SNL/KAFB area is found in the ancestral Rio Grande fluvial facies to the west and alluvial fan facies to the east. Hawley and Haase (1992) estimated that hydraulic conductivities in the USF could range from less than 0.3 ft/d in an alluvial fan facies to more than 30 ft/d in the fluvial facies. Thorn et al. (1993) presented a summary of pumping test results, mainly from production wells located in the productive channel deposits, that had hydraulic conductivities ranging from about 7 to 150 ft/d. SWHC Project pumping tests yielded values of between 46 and 147 ft/d. Table 2.1 summarizes hydraulic conductivity data obtained from wells in the ancestral Rio Grande fluvial facies.

Hydraulic conductivity data for the alluvial fan facies are available from pumping tests performed on water supply wells located east of the eastern limit of the fluvial facies. These wells are screened over large intervals which may include intervals of fluvial facies that intertongue with the predominant alluvial fan facies. Table 2.2 summarizes hydraulic conductivity data obtained in wells completed in this facies.

Calculated storage coefficients are available from pumping tests in the Ridgecrest well field, a pumping test at the SNL CWL, and from the analysis of draw-down recovery data at monitoring well TA2-NM1-595, resulting from pumping of KAFB-11. Table 2.3 summarizes these values. Plate 1 shows geologic units present at the regional water table and wells with pumping tests.

2.2.3 Groundwater Flow Patterns

Groundwater flow includes both downward recharge flow in the exposed bedrock areas in the eastern part of the SNL/KAFB (not explicitly considered in the numerical model), in the arroyos and lateral (predominantly east to west) flow through the shallow alluvial and bedrock aquifers on the east, and across the north-south fault complex. There are two complicating factors for the conceptual model of groundwater flow beneath SNL/KAFB. The first factor is the impact of the north-south fault complex on the overall flow system. This fault complex bisects SNL/KAFB and has a very apparent impact on the area-wide flow system. This impact is seen in the large changes in water level as the faults are crossed from east to west.

The second important factor is the continual removal of large amounts of groundwater for the municipal water supply for the City of Albuquerque. Groundwater withdrawal by water supply wells from the City of Albuquerque and KAFB has resulted in significant changes to the groundwater flow regime in the SFG over the past 30 years as discharge exceeds recharge for this portion of the Albuquerque Basin (Thorn et al. 1993). Groundwater flow at SNL/KAFB has been altered from a principally westward flow to northwestward and northward flows along the western and northern portions of KAFB (Figure 2.16). The long trough extending to the south suggests that deposits of greater transmissivity exist in this area and the possibility that the Rio Grande fault is isolating the area from the hydraulic influence of the river.

Water level declines have been occurring within the Albuquerque Basin since the 1960's, when significant increases in groundwater withdrawal began. Basin-wide declines from steady-state conditions have been estimated to range from 20 to 60 ft (Thorn et al. 1993). The greatest declines are to the east of the eastern limit of fluvial deposits of the ancestral Rio Grande (Thorn et al. 1993).

Since the mid-1980's, water levels have been collected from monitoring wells on SNL/KAFB. Hydrographs from these data indicate groundwater levels are declining at rates of between 0.2 and 3.0 ft/yr within the upper unit of the SFG in HR-1. On KAFB, the rate of water level declines generally increases westward from the Sandia Tijeras fault zone and northward near water-supply production wells. Based on estimates of steady-state conditions by Thorn et al. (1993), groundwater has declined from 60 to 140 ft across the base, approximately 100 ft at the northern KAFB boundary to approximately 50 ft at the southern KAFB boundary (Thorn et al., 1993). Groundwater level surveillance by SNL since approximately 1990 (SNL 1995) indicates that wells completed west of the eastern extent of fluvial deposits have water level declines of 1.0 to 3.0 ft/yr, whereas wells on the east display declines of 1.0 ft or less per year (Figure 2.17). These groundwater declines represent only the upper 100 ft or less of the upper unit of the SFG aquifer, because most of the wells on SNL/KAFB are water-quality monitoring wells and have short screen lengths in comparison to the thickness of the aquifer.

Surface water flows through the SNL/KAFB area in arroyos, primarily Tijeras Arroyo and Arroyo del Coyote. These arroyos also function as local sources for groundwater recharge. Precipitation that falls on the area between arroyos either runs off into the arroyos or is evapotranspired (the combined processes of evaporation and transpiration of water by plants).

Currently it is thought that essentially no groundwater recharge occurs in the interarroyo areas west of the foothills. Arroyos outside of Tijeras and Arroyo del Coyote drainages almost never reach the Rio Grande. These arroyos widen into pseudo-playas from which the water evaporates. The western portions of these arroyos are underlain with caliche, even where well channelized, indicating that they seldom flow and are not natural recharge sources. Near the mountains, flows in the southern arroyos may be more frequent, and channel-bottom materials may be more permeable, thus allowing natural recharge.

2.3 Conceptual Model Summary

The salient points of the conceptual model are summarized as follows:

- Channel deposits of the ancestral Rio Grande extend through the west SNL/KAFB area in a north-south direction.
- Alluvial fan deposits extend from the east into the ancestral Rio Grande deposits.
- Sharp contrasts in hydraulic properties occur as a result of the abutment of lithologies deposited in distinctly different environments.
- Recharge occurs mainly from Tijeras Arroyo, Arroyo del Coyote, and the Manzano Mountains mountain front, with some component of flow from the bedrock.

- Sediments decrease in hydraulic conductivity with depth as the USF grades into the Middle Santa Fe (MSF) and Lower Santa Fe (LSF), which were deposited under different (mainly low-energy alluvial) environments.
- Currently the water table is in the USF.
- Large amounts of groundwater flow are from storage release (i.e., dewatering).
- Pumpage greatly exceeds recharge from all sources (precipitation, Rio Grande leakage).
- Fault systems in the SFG probably act as restrictions to groundwater flow, abutting low-flow lithologies and cementation of the fault gouge.

Table 2.1 Hydraulic Conductivity for Ancestral Rio Grande Fluvial Facies of the Santa Fe Group

Data Source	**Data Type**	**Hydraulic Conductivity (ft/day)**
	Data from Other Publications	
Hawley and Haase (1992)	Estimated for the fluvial facies	>30.0
KAFB IRP Investigation (USGS 1993)	Slug Test Analysis (KAFB IRP Monitoring Wells in Fluvial Facies)	0.2 to 10.5
Water Supply Well Analysis (GMI 1988a, 1988b)	Pumping Test Analysis (Yale and Burton Well Fields)	12.0 to 121.5
	Data from SNL/ER Projects	
Site Wide Hydrogeologic Characterization Project (SNL/NM 1996)	1995 Pumping Test Analysis at PL-2 and MRN-1 (Appendix D)	46.6 to 147.1
	1995 Slug Test Analysis at PL-2 and MRN-1 (Appendix D)	0.26 to 2.6

Table 2.2 Hydraulic Conductivity for Alluvial Fan Facies of the Santa Fe Group

Data Source	Data Type	Hydraulic Conductivity (ft/day)
Data From Other Publications		
Hawley and Haase (1992)	Estimated for Alluvial Fan Facies	<0.3
KAFB IRP Investigation (USGS 1993)	Slug Test	0.08 to 13.0
Water Supply Well Analysis (GMI 1988c)	Pumping Test (Ridgecrest Well Field)	9.66 to 44.7
Data from SNL/NM ER Projects		
Chemical Waste Landfill (IT 1985, SNL/NM 1993, 1995a)	1990 pumping test at MW-2A	0.39
	1990 laboratory analysis of samples from MW-4	0.01 to 10.8
	1985 slug tests at MW-1, MW-2, and MW-3	0.07 to 0.09
	1994 slug tests at BW-3, BW-3, and BW-4A	0.014 to 0.031
	1995 slug tests in MW-1A, MW-2A, MW-3A, MW-5 (upper), and MW-6 (upper)	0.02 to 0.33
	1995 slug test in MW-2B (lower)	6.74
	1995 pumping tests in BW-4A	0.01
	1995 pumping tests in MW-2B (lower)	6.74
	1995 pumping tests in BW-4A	0.01
	1995 pumping tests in MW-2B (lower)	2.16
	Observation wells MW-5 (lower and MW-6 (lower) during 1995 pumping test in MW-2B (lower)	25.9 to 27.4
Mixed Waste Landfill (SNL/NM MWL Project Files)	1994 pumping test in MW-4 (upper)	0.072
	1994 pumping test in MW-4 (lower)	1.48
	Recovery data from water-sampling operations (MW-1, MW-2, and MW-3, and BW-1)	0.001 to 0.055
LWDS and TA-4 (SNL/NM LWDS and TA-V Project Files	1995 slug tests at LWDS MW-01 and MW-02; TA5 MW-01 and MW-02	0.04 to 2.38
Site-Wide Hydrogeologic Characterization Project (SNL/NM 1995 and 1996)	1994 Pumping Test at SFR-3P (HR-2)	10.34
	1995 slug test at KAFB-0311	6.14
	1994 analysis of draw-down recovery data from TA2-NW1-595 (well response due to pumping at KAFB-11)	14.5

Table 2.3. Storage Coefficient Values from Aquifer Tests in the Santa Fe Group

Data Source	Data Type	Storage Coefficient (dimensionless)
Data from Other Publications		
Water supply well analysis (GMI 1988c)	Pumping test analyses (Ridgecrest well field)	0.001
Data from SNL/ER Projects		
Chemical Waste Landfill (SNL/NM 1995a)	1995 Pumping test at CWL (MW-5 [lower] and MW-6 [lower])	0.00017 to 0.000033
Site-Wide Hydrogeologic Characterization Project (SNL/NM 1996))	1995 analysis of draw-down recovery data from TA2-NW1-595 (well response due to pumping at KAFB-11)	0.00024

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3.0 GROUNDWATER FLOW MODEL CONSTRUCTION

A general protocol has been developed for model application (Anderson and Woessner, 1992; ASTM Standard Guide D5447-93, "Application of a Ground-Water Flow Model to a Site-Specific Problem"). This protocol includes code selection issues, model conceptualization and design, calibration, sensitivity analysis, prediction, and reporting. Figure 3.1 illustrates the steps in the protocol. The approach taken in this analysis follows this protocol. The verification and postaudit steps are typically not performed. Verification is the comparison of independent model prediction to data not used in calibration. It is often impossible to verify a model, because usually only one set of field data is available, which is needed for calibration (Anderson and Woessner, 1992). A post audit is the comparison of model prediction to reality some period of time (often several years) after the modeled action is implemented.

3.1 Code Selection

The most widely used computer program for groundwater flow modeling in the world (Rumbaugh and Ruskauff, 1993) is the USGS MODFLOW code (McDonald and Harbaugh, 1988). Andersen (1993) describes the code verification with several analytic and comparisons with other numerical models. MODFLOW is capable of simulating transient or steady-state groundwater flow in one, two, or three dimensions. A number of different boundary conditions are available, including specified head, areal recharge, injection or extraction wells, evapotranspiration, drains, and rivers. MODFLOW simulates groundwater flow using a block-centered, finite-difference approximation for the solution of the governing equation for flow. Aquifers can be simulated as unconfined, confined, or a combination of unconfined and confined. The finite-difference equations may be solved with a strongly implicit procedure (SIP), slice-successive over-relaxation (SSOR), or preconditioned conjugate gradient (PCG) methods. MODFLOW was selected for use on this project because of its widespread scientific and regulatory acceptance and the number of commercially available software tools to expedite data preparation and output analysis. In addition, third-party modifications allow the addition of various extra features, including solute transport and unsaturated flow. Finally, the use of the Albuquerque Basin Model (ABM) in conjunction with MODFLOW provided the following advantages:

- MODFLOW has been extensively used to analyze groundwater flow conditions in New Mexico, and thus state and municipal agencies are familiar with it.
- Data input for the ABM MODFLOW already existed and were available for use. This data could easily by modified to meet SNL/KAFB requirements.

- The SNL/KAFB model can be directly tied to the basin physical boundaries on the west and east and a reasonable representation of the effects of the other boundaries and pumping included on the northern and southern boundaries in a fashion consistent with regional trends.
- The ABM is used by the City of Albuquerque for water resources planning and will be periodically updated. SNL/KAFB can work closely with both agencies through the Albuquerque Basin Contact Group to keep the model current in the area.
- The State Engineer may also use the ABM to support water resources planning and adjudication of water rights in the Albuquerque Basin. Therefore, using MODFLOW would be consistent with the primary state and municipal agencies that use models and with whom SNL/KAFB interacts.

Groundwater capture zones and flow paths were delineated with the MODPATH (Pollock, 1989) computer program. MODPATH, developed by the USGS, works in conjunction with MODFLOW, using the simulated heads and flows to compute the velocity field. With the particle tracking technique, the movement of a parcel of water in the aquifer is computed using the simulated velocity field. Particle tracking is a simple form of contaminant transport analysis that disregards the effects of dispersion, retardation, and other chemical reactions. Particles can be moved forward with the flow field in a manner akin to a marble rolling down a plane surface to determine their final destination, or particles can be moved backwards (reverse) from a final location to an origin. Each type of analysis is useful and presents different aspects of the situation.

A primary difficulty with numerical models such as MODFLOW is quality control when preparing large datasets. These datasets are filled with numbers that must be formatted precisely for the program to execute; incorrect entries may cause the program to crash, or worse, execute improperly with no warning. To help alleviate this problem, a class of software known as *preprocessors* has been developed to aid in model input. Preprocessors help streamline data preparation and provide better quality control. The initial ABM data sets prepared by the USGS were constructed using the ARC/INFO GIS as described in Kernodle et al. (1995). The preprocessor *Groundwater Vistas*, version 1.61 by Environmental Simulations, Inc. (1996) was used to prepare data sets for the final phase of this analysis. Model output is seldom directly usable, and must be *postprocessed* into some usable format. *Groundwater Vistas* includes built-in support for contouring simulated heads, velocity vector maps, and pathline plotting from MODPATH particle tracking results. In addition, ARC/INFO, in conjunction with ArcView, was used to process input and output for display. *Groundwater Vistas* stores the model design in a model-independent format, so the model design can be translated to more complex codes if it should become necessary in the future.

3.2 Calibration Strategy and Data

Calibration targets are a set of field measured values, typically groundwater hydraulic heads, to which model predicted values are compared. The goal in selecting calibration targets is to define a set of measurements that are reliable and spatially distributed throughout the model area. Comparisons should be made between point measurements of hydraulic heads rather than maps of these heads, because the contour lines are the result of interpretation of data points and are not considered basic data in and of themselves. The groundwater flow model should be true to the essential features of the conceptual model and not to their representation (ASTM Standard Guide D5490-93).

Water levels have been declining in the Albuquerque Basin since the 1960's, as discussed in section 2.4.4. Under these conditions the time-varying nature of flow is required to analyze groundwater conditions at SNL/KAFB. A transient simulation typically begins with steady-state initial conditions and generates a set of computed heads for each time step. It is important to recognize that the initial conditions for a transient simulation must be determined by modeling since this assures that the initial heads, model boundary conditions, and aquifer parameters are consistent. If an interpretation (e.g., contour map) were used as initial conditions, the model response in early time would reflect not only the conditions under study but the adjustment of model head values to offset the lack of correspondence between model boundary conditions, aquifer properties, and the initial head field (ASTM Standard Guide D5610-94 "Defining Initial Conditions in Ground-Water Flow Modeling"). Transient simulations are more complicated than steady-state simulations for the following reasons:

1. An additional aquifer property, storage coefficients, must be specified.
2. Errors in initial conditions can propagate into the transient analysis.
3. Pumping and other effects may propagate out to model boundaries and cause the boundary conditions to become inappropriate.
4. The time dimension in addition to the space dimension must be discretized.
5. More input and output must be managed, and data management becomes complex.

Transient calibration was conducted for the period from January 1, 1980, to March 31, 1995. Data existed from about 1987 onward. The USGS made its predictions by simulating forward from 1980, and the same convention was followed here. A total of 43 wells was used for calibration targets, with 1 to 80 measurements available for each well, for a total of 1,378 observations used for the calibration. Table 3.1 summarizes this information. Initial conditions and calibration goals are discussed further in sections 3.5 and 4.0, respectively.

3.3 Model Discretization

3.3.1 Spatial Discretization

The finite-difference solution of the governing equations requires that the system (conceptual model of the aquifer) be divided into a set of discrete blocks. This discretization allows each block to be assigned a different set of properties. These blocks form the model grid with a node located at the center of each block. The process of dividing the area of the aquifer to be simulated is called discretization. Water levels computed for each node are the average over the volume of each block. Thus, adequate discretizaiton is required to resolve features of interest and yet not be computationally burdensome. An algebraic equation that describes groundwater flow is written for each block in terms of the surrounding blocks and results in a set of linear equations. The set of linear equations is iteratively solved until the change between iterations meets a preset criterion established by the analyst; a rule of thumb is to set the convergence criteria one to two orders of magnitude lower than the level of accuracy desired in the head results (Anderson and Woessner, 1992).

The empirical 50-percent rule was followed in the discretization process (Anderson and Woessner, 1992). That is, no block changed size more than 50 percent relative to the adjacent blocks. This is necessary to control numerical truncation errors and preserve fluid mass balance. The finite-difference method assumes that aquifer properties are constant within a block and that hydraulic heads vary linearly between nodes. Thus, smaller blocks were used over most of the area where the influence of pumping causes the hydraulic head surface to curve rapidly. Block dimensions were uniform in the column, or x direction (east-west orientation), at 656 ft and from 650 ft in the north to 3,700 ft in the south in the row, or y direction (north-south orientation). The grid was designed so that boundary conditions would correspond with physical or hydrologic boundaries where possible (e.g., Rio Grande, basin boundary to the east). See Figure 3.2.

Vertical discretization may be approached using either a quasi-three-dimensional or fully three-dimensional technique. In the first approach, the aquifer system is considered to be an alternating series of permeable and impermeable beds, with the primary resistance to vertical flow occurring in the impermeable beds separating the permeable layers. The low-permeability unit is represented mathematically as a resistance term for fluid flow between the permeable units. Alternatively, each geologic unit, regardless of its properties, is represented in the model. The fully three-dimensional approach was used in the KAFB model. Thus all the units in the SFG were each represented in the model as a layer. The top of the model was the pre-1901 water table.

Each of the upper four layers in the model are 20 ft thick at the Rio Grande and approximately 30 ft thick at the northeast boundary of the SNL/KAFB model (Figure 3.3). The thickness of layers 5 through 11 is constant across the model. Individual layer thickness ranges between 50 ft in layer 5 to 500 ft in layer 11. The purpose of the relatively thin upper layers is to account for surface water/groundwater interaction (Kernodle et al. 1995). The total modeled thickness includes the major pumping zones in Albuquerque within the SFG.

3.3.2 Temporal Discretization

Just as it is desirable to use appropriately sized grid blocks, it is also desirable to use an appropriate time-step size for transient simulations. A good order of magnitude estimate for the initial time step is obtained by assuming the aquifer is homogenous and isotropic with a regular grid. The critical time step, t_c, is defined as follows (deMarsily, 1986):

$$\Delta t_c = Sa^2 / 4T \tag{3.1}$$

where

S is storativity (-),

T is transmissivity (ft2/d),

a is a representative grid block size.

In more general applications, t_c can be approximated by selecting a representative grid block dimension *a* and properties. The transient solution is sensitive to rapidly fluctuating pressures caused by introducing a hydraulic stress, making it important to use time steps on the order of t_c to capture the early response of the system even if one is interested only in the solution at later times. For instance, using a storativity of 1×10^{-4}, a 600 ft grid block spacing, and a transmissivity of 4,500 ft^2/d; t_c is 172 seconds. Clearly, this time step size is not practical to use for all time steps in the transient simulation. Although time steps can be increased as a geometric progression with a ratio of 1.2 to 1.5 (Anderson and Woessner, 1992) this will still result in prohibitive simulation run times. Alternatively, the results for the first few time steps could be ignored. If this approach is taken, the solution should proceed through five time steps, during which there are no significant changes in sources, sinks, or boundary conditions before the solution is considered accurate (deMarsily, 1986). The SNL/KAFB model uses time stepping identical to the USGS ABM. The USGS did not follow the above criteria, but their approach appears to be adequate considering the available information on pumping and water levels. Practically speaking, the effects of using the USGS temporal discretization are probably minor. Any computational errors introduced will be evident as mismatch between model and data.

The period between January 1, 1980, and March 31, 1995, was divided into 30 stress periods and 414 time steps. A stress period in MODFLOW terminology is a time span in which all boundary conditions remain constant. The first stress period was from January to August 1980 divided into eight time steps. Thereafter stress period were divided into six-month periods with seven time steps to mimic the pumping and water-use cycle in the basin, which declines abruptly in the fall through winter and peaks during summer. The time step multiplier was 1.5, which, using the formula presented by McDonald and Harbaugh (1988), gives an initial time step size of 5.7 days, with successive time steps of 8.53, 12.8, 19.2, 28.8, 43.2, and 64.8 days.

3.4 Boundary Conditions

Once the area of interest has been discretized, it is implicitly assumed that the rest of the surrounding area can be ignored. The model, however, must account for the effects of external conditions that may affect the area of interest and allow water to flow in or out. These effects are accounted for by the use of appropriate boundary conditions. Model boundaries should be chosen to correspond to natural hydrologic boundaries of the groundwater flow system where identifiable.

The specified rate, or flux, conditions allow a given quantity of water to be applied to a unit area of the model per unit time. The specified-rate condition is used to represent both flow from the ABM to the SNL/KAFB submodel, recharge, and wells in MODFLOW. In order to remove the SNL/KAFB area from the ABM, either specified head or specified flux conditions could be used to link the ABM to the submodel. The time-weighted average flow in each cell on the submodel boundary was computed using the ABM. One average value was computed for each cell during each stress period from 1980 to 1995. The well package was used to introduce these flows. A comparison of ABM and SNL/KAFB submodel simulated heads showed that the difference was within 1 ft for all layers. Irrigation and septic-return flow were simulated with the recharge package.

Private water-supply wells, KAFB water-supply wells, and City of Albuquerque wells are located within the SNL/KAFB model area. The majority of the City of Albuquerque wells are located to the north and northwest of KAFB. The KAFB well fields are located in the middle of the SNL/KAFB model. Private wells are located west of KAFB and along the south boundary of the model. Well rate data as used in the ABM by the USGS were maintained in the submodel.

Value-dependent flux boundary conditions are implemented as the drain, evapotranspiration, general head, or river conditions in MODFLOW. These boundaries are called the value-dependent flux condition because the flux entering or exiting the groundwater flow model is dependent upon the head difference between the value computed at the model boundary and a source of water maintained at a constant level outside the model. The source is visualized as being connected to the model through a conduit of aquifer material of specified length. This type of boundary is more flexible than the constant head or constant flux boundaries because both the simulated flow rate and head can vary. River, drain, and evapotranspiration boundaries were used in the SNL/KAFB model.

The Rio Grande and its drain system were represented with the river and drain packages. For the transient calibration, the Rio Grande stage was required for each stress period. The same stage was used for each stress period (wet and dry), with the number of active river cells in dry conditions about one fourth of that in wet conditions to reflect lower river flow. These boundaries were not altered since it is likely that the USGS has the best information on them.

3.5 Initial Conditions

The ABM was first calibrated to estimated steady-state conditions along the inner valley of the basin from 1901, and then those results were used as the starting point for the transient simulation from 1901 forward. Before removing the SNL/KAFB subarea from the ABM, some gross adjustments were made (e.g., areas of higher hydraulic conductivity representing the ancestral Rio Grande not in the ABM) and the model run forward from 1980 conditions. A more rigorous approach would have been to recalibrate the 1901 steady-state model with the changes and then run it forward through 1995. However, the ABM results for wells near and on SNL/KAFB show general agreement between simulated and observed heads, and it is felt that, given the project goals and the inherent uncertainty in this problem, that this approach is acceptable. Sensitivity of the model to initial conditions is investigated in section 4.4.4.

3.6 Parameter Zonation

Simulation of groundwater flow requires knowledge of the hydraulic properties of the aquifer. The areal distribution of aquifer properties (e.g., hydraulic conductivity) is required as input to MODFLOW for each grid block in the model. Clearly, no amount of site characterization will completely determine aquifer properties, and some simplification must be made. The technique of parameter zonation was used to define the spatial variation of aquifer parameters. The method requires the delineation of zones within which a constant value of a parameter is assigned. When possible, the zones are chosen based upon hydrogeologic information such as the nature and thickness of strata. The average value and the extent of each zone were determined during the calibration process.

3.7 Initial Model Parameters

Initial parameter values were obtained from the ABM as described by Kernodle et al. (1995). Plates 2 and 3 show the initial parameter value and distributions in the ABM area of the submodel. Results from this model and its fit to the SNL/KAFB data are discussed in section 4.2.1, and the reasons for the changes made during calibration are discussed in sections 4.2.2, 4.2.3. Model sensitivity to various parameters is analyzed in section 4.2.4.

Table 3.1 Summary of Data Used for Calibration

Well Name	Period of Record
CWLBW3M	Oct. 88-Dec. 95
CWLMW1A	Oct. 88-Dec. 95
CWLMW2	Jan. 86-Aug. 95
CWLMW3A	Oct. 88-Aug. 95
MWLBW1	Nov. 89-Nov.95
MWLMW1	Jan. 89 - Nov. 95
NWTA-03	Nov. 89-Nov. 95
SWTA-03	Nov. 89-Nov. 95
LWDSMW1	Nov. 93-Nov. 95
LWDSMW2	Mar. 94-Nov. 95
TAVMW1	Jun. 95
TAVMW2	Jun. 95-Nov. 95
AVN1	Mar. 95-Nov. 95
AVN2	Mar. 95-Nov. 95
KAFB-9	Jun. 89- May 92
KAFB-10	Jan 89-Jul 95
KAFB-0107	Jul 89-Aug 95
KAFB-0213	Jul 89-Aug 95
KAFB-0214	Apr 92-Dec 93

KAFB-0215	Apr 92-Dec 93
KAFB-0216	Aug 92-Dec 93
KAFB-0217	Aug 92-Dec 93
KAFB-0218	Jul 92-Dec 93
KAFB-0501	Jan 91-Dec 95
KAFB-0502	Jan 91-Dec 95
KAFB-0503	Jan 91-Dec 95
KAFB-0504	Jan 91-Dec 95
KAFB-0901	Dec 90-Nov 95
KAFB-0902	Dec 90-Nov 95
KAFB-1001	Jul 92-Jun 96
KAFB-1002	Jul 92-Jun 96
KAFB-1003	Jul 92-Dec 93
KAFB-1004	Jul 92-Dec 93
KAFB-1005	Jul 92-Jun 96
MVMWJ	Jul 89-Dec 95
MVMWK	Jul 89-Dec 95
TA2NW1595	Sep 93-Sept 95
San Jose 3	Mar 90-Sep 93
San Jose 9	Mar 90-Sep 95
KAFB-310	Mar 91-Mar 95
Chava	Mar 90-Mar 95
SBLF-1	Mar 90-Mar 95
SBLF-4	Mar 90-Mar 95
Yale 3	Mar 90-Mar 95

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4.0 GROUNDWATER FLOW MODEL CALIBRATION

Calibration of a groundwater flow model is the process of adjusting model parameters until the model reproduces field-measured values of head and flow rates. Successful calibration of a flow model to observed heads and flow directions enables the model to be used in the prediction of groundwater flow paths and heads.

Model calibration is judged by quantitatively analyzing the difference (called a residual hereafter) between observed and model-computed values. Several statistical and graphical methods are used to assess the model calibration. These statistics and methods are described in greater detail in ASTM (American Society for Testing Materials) standards D5490-93 "Comparing Ground-Water Flow Model Simulations to Site-Specific Information." The mean error (ME) is defined as:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i \qquad \textbf{(4.1)}$$

where
h_m is measured hydraulic head, and
h_s is simulated hydraulic head.

A positive mean error indicates that the model has systematically underestimated heads, and a negative error indicates the reverse. It is possible to have a ME near 0 and still have considerable errors in the model (i.e., errors of +50 and -50 give the same mean residual as +1 and -1). Thus an additional measure, standard deviation (SD) of the errors, is used to quantify model goodness of fit. It is defined as follows:

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2} \qquad \textbf{(4.2)}$$

A large SD means that there is wide scattering of errors around the mean error.

Finally, the sum of the residuals squared is used as the objective function in parameter estimation and is defined as:

$$SS = \sum_{i=1}^{n}(h_m - h_s)_i^2 \qquad \textbf{(4.3)}$$

In addition to summary statistics, calibration is also assessed using a variety of graphical methods. Two commonly used graphical methods to assess model calibration are a plot of observed versus simulated water levels and a histogram of the errors. If the observed and simulated water levels matched exactly (i.e., perfect calibration), the data would fall on a straight line with a slope of 1. In a real-world calibration, however, there will be some scatter of residuals about the line of perfect match. Bias is revealed by clustering of data above (overprediction, or too wet) or below (underprediction, or too dry) the perfect-fit line. A histogram is useful for diagnosing the variability of model errors.

The time periods for calibration and the available targets were discussed in section 3.2. These measurements have an inherent error component due to instrument and sampling scale limitations. It is important to define the level of plausible uncertainty in order to know when the model calibration is as good as warranted by the data and to set goals in the context of the above statistical measures.

There are several types of errors associated with water-level measurements and their calculation by a model. These errors require realistic assessment so that achievable accuracy can be quantified. Errors associated with field measurements are typically about 0.04 ft, and elevation surveys commonly accumulate errors that average about 0.1ft (Anderson and Woessner, 1992). Another type of error is that related to the scale of measurement of an observation well. Averaging of water levels occurs over the portion of a well open to the aquifer. A well completed in only part of an aquifer may give a different value than a fully screened well at the same location. For instance, CWL MW-6U and CWL MW-6L are located about 20 ft apart at ground surface, with screens separated by 55 ft vertically, and have groundwater levels about 3 ft different. Error from small-scale heterogeneity that cannot be modeled may also occur. This is because the grid blocks in a model represent average properties within the block, but field measurements may be influenced by small-scale variations. Gelhar (1986) presents a technique for estimating what this error is for a three-dimensional flow system. The error from unaccounted-for, small-scale heterogeneity is estimated at about 0.6 ft. Finally, if the calibration target location does not coincide with the center of the grid block, there will be an interpolation error. A maximum interpolation error of between 0.65 and 4 ft is estimated from block size of 650 and 3000 ft, respectively. The sum of all the above errors is 4.74 ft. Alternatively, a general rule of thumb is that no target should have an error greater than 10 to 15% of the total measured change in head across the model domain. The total measured change for the calibration period is 94 ft giving an allowable error of 9.4 ft.

Based upon the calibration goal, the following calibration criteria were established:

- The ME be less than 10 percent of the total measured head change, or 9.4 ft.
- The ratio of the SD to total head change be less than 10 percent, for a SD of 9.4 ft.
- The SS be about the calibration level squared times the number of observations in the SNL/KAFB model, or 110,000 ft^2.

Table 4.1 summarizes these goals and what was achieved during calibration.

4.1 Parameter Estimation Technique

Two approaches are typically used to calibrate models: trial-and-error and automated inverse procedures. The trial-and-error approach is tedious and subject to the analyst bias (Anderson and Woessner, 1992). The automated inverse procedure is similar to the trial-and-error approach in that a large number of simulations are run to determine model sensitivity to selected parameters. However, the inverse procedure checks the computed heads and adjusts the model parameters in a systematic fashion to minimize the deviation between observed and computed heads. The advantage to using an automated calibration technique is that it provides a structured, systematic approach to the calibration process, and it allows the analyst to focus more on conceptual model development (Anderson and Woessner, 1992; Olsthoorn and Kamps, 1996). In addition, inferences can be drawn from the results of the appropriateness of the model conceptualization in describing the physical system when an automated inverse method is used (Poeter and Hill, 1996). For instance, extremely large confidence intervals around the estimated value can reveal that the problem is not well constrained by the data.

Most of the calibration was done by trial and error by identifying facies distribution and then assigning representative values for model parameters derived from site-specific and regional data. A limited automated inverse analysis was conducted to aid in refining parameter values and to test the conceptual model and the resulting distribution of associated parameters.

The PEST (parameter estimation) code by Watermark Computing, Inc. version 1.08 was used in conjunction with MODFLOW to perform parameter estimation. PEST uses a nonlinear regression procedure known as the Guass-Marquardt-Levenberg technique (Watermark 1994; Hill 1992) to minimize the deviations between a set of observations and model-computed results. PEST works by taking control of MODFLOW and modifying its data sets as it runs. For more details see the PEST User's Guide (Watermark 1994).

4.2 Calibration Results

4.2.1 Initial U.S. Geological Survey Model Results

The initial model based upon USGS regional data did not match well. In particular, the impact of pumping was too subdued, and the draw-down trough was poorly developed. Water-levels were systematically overpredicted, although the gross flow field flow direction was correct. A plot of observed versus model computed water levels is shown in Figure 4.1. Figure 4.2 shows a histogram of the residuals. About 45% of the observations are within the error bound established; however, there is a strong bias toward overprediction as can be seen by the large amounts of data on the left of the plot. The summary calibration statistics were ME of -7.6 ft, SD of 9.65 ft, RSS of 230,000 ft^2, and a ratio of SD to total head change of 10.2% (see Table 4.1). Figure 4.3 shows the simulated and mapped flow field in model layer 4, which is reasonably representative of the regional system and has the most data. Plates 2 and 3 show the distribution of model parameters.

4.2.2 Changes to the Model

Based upon the conceptual model developed by the SWHC Project, the following major changes were made to the numerical model:

- An extensive north-south oriented region over most of SNL/KAFB was treated as axial channel deposits.
- Low hydraulic conductivity sediments representative of alluvial fan deposits (measurements taken at CWL) were added along the eastern margin of the model.
- Recharge along Tijeras Arroyo was reduced by over an order of magnitude to the value of 2.2×10^6 ft^3/yr estimated by the SWHC Project.

The impact of recharge along Tijeras Arroyo was further investigated by using the SWHC conceptual geologic model with both the USGS and SWHC estimates of recharge.

4.2.3 Transient Calibration (January 1, 1980 to March 31, 1995 Data)- USGS Tijeras Arroyo Recharge

Figure 4.2 shows a histogram of the residuals. Of the 1,378 calibration targets, about 43 percent were within the error bound established, with some bias towards overprediction (too much water in the model).

The distribution of errors shows less bias than the base USGS model with less spread in the overall errors. A plot of the observed versus model computed water levels for January 1980 to March 1995 is shown in Figure 4.4. In general, the data are scattered symmetrically around the line of perfect match, although overall there is an overpredictive (too wet) bias. The group of points at the upper right hand of the plot is the data from KAFB-9. The model match to this point could be improved by increasing hydraulic conductivity in the area.

The simulated and mapped water levels in layer 4 are shown in Figure 4.5. In general the observed and simulated water levels match reasonably. The quantitative calibration criteria established in section 3.3 are all met or exceeded, with the mean residual of -2.91 ft, SD of 6.31 ft, SS of 74,400 ft^2, and ratio of SD to total observed head change of 6.7 percent (see Table 4.1); therefore the model is considered calibrated to existing conditions. The distribution of hydraulic conductivity and leakance for this model is shown in Plates 4 and 5.

4.2.4 Transient Calibration (January 1, 1980 to March 31, 1995 Data)- SWHC Project Tijeras Arroyo Recharge

A plot of the observed versus model computed water levels for January 1980 to March 1995 is shown in Figure 4.6. Simulated and observed hydrographs are shown in Appendix A. In general, the data are scattered symmetrically around the line of perfect match, although overall there is an underpredictive (too dry) bias. The group of points at the upper right hand of the plot is the data from KAFB-9. Figure 4.2 shows a histogram of the residuals. About 45% of the errors are within the established bounds, with some underpredictive (too little water in the model) bias present.

The simulated and mapped water levels in layer 4 are shown in Figure 4.11. The quantitative calibration criteria established in section 3.3 are all met or exceeded, with the mean residual of 4.25 ft, SD of 6.36 ft, SS of 90,100 ft^2, and ratio of SD to total observed head change of 6.7% (see Table 4.1); therefore, the model is considered calibrated to existing conditions. The distribution of hydraulic conductivity and leakance for this model is shown in Plates 6 and 7.

4.2.5 Final Sensitivities

The calibrated model has over 100 different inputs that describe the hydrogeologic regime and could be adjusted to improve calibration. Obviously, some assessment of which parameters are important is required to understand the important aspects of the numerical implementation of the conceptualization.

This was done by perturbing the parameter and noting the resulting change in the SS. From this a sensitivity coefficient was computed as follows (Freeze and Reeves, 1996):

$$S_i = \frac{|\,\Delta SS\,|}{\Delta\,\text{parameter}_i}\ (\text{initial parameter}_i\ \text{value})$$

Note that this is the ratio of the absolute value of the incremental change in SS divided by the fractional change in the parameter value. This removes the difference that occurs when comparing results from parameters that have many orders of magnitude differences and different units (e.g., recharge with a value of 0.001 and transmissivity with a value of 1,000's). Other forms of sensitivity analysis are described in ASTM Standard Guide D5611-94 "Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application." It is important to note that the sensitivity of a parameter may change as its value does. A parameter that initially is too high may not show any sensitivity over the initial range investigated, but as its value is lowered it may become sensitive.

Table 4.2 shows the results of this sensitivity analysis for 26 of the numerical model parameters. The most sensitive parameters are initial head, specific yield, leakance zone 2660 (corresponds to a value of 2.663×10^{-4} 1/d) hydraulic conductivity zone 4 (alluvial fan near TA-V in the northeast quadrant of the model), and specific storage in layers 6 to 11. The deposits of the Rio Grande to the west of the axial channel deposits are also sensitive, probably because they control the influence of the Rio Grande on the shape of potentiometric surface. Since the model is somewhat sensitive to the representation of these deposits, it would seem reasonable that the Rio Grande fault system in the same general area should also be a sensitivity parameter. That this is not observed suggests that the representation of the fault may be inadequate.

Historical initial steady-state heads are not known outside of the inner Rio Grande valley; any uncertainty from this source is not reducible. The sensitivity of specific yield and specific storativity confirms the conceptual model that has large amounts of flow from storage (i.e., dewatering the basin) as the primary source of water pumped from the SFG. Specific yield and specific storativity were assumed by the USGS. Comparison of SWHC Project pumping tests with the assumed value of specific storage suggests that it is reasonable. However, the model is more sensitive to specific yield than specific storage (which is reasonable since more water is released from storage per unit decline of the potentiometric surface under water table than confined conditions), which is not well characterized on SNL/KAFB or in the basin in general. Thus it is likely that compensating errors between storativity, transmissivity, and water budget exist.

To some extent the sensitivity of parameters is controlled by the distribution of the data. For instance, where Tijeras Arroyo runs near TA-2 (see Figure 1.1) hydraulic gradients are steep, and observation wells tend to be clustered. This combination means that slight parameter changes can produce large changes in the potentiometric surface shape, greatly affecting a relatively large amount of the calibration data.

4.3 Flowpath Analysis

Particle tracking analysis with the calibrated flow field was conducted to assess groundwater pathways and containment. The trajectories of these particle tracks generally describe the migration of dissolved constituents in groundwater. It is possible that local preferential flow paths can cause the true paths to be different than those estimated by the model. However, the general flow paths should be similar to those suggested by the model results.

The MODPATH program (Pollock, 1989), a companion program to MODFLOW, was used for the particle tracking analysis. MODPATH uses the computed water levels and flow rates between cells to calculate an average interstitial velocity. In general, the velocity can be computed as follows:

$$V = K\,I/n$$

where

V is the average velocity of a particle of water (ft/d),

K is the hydraulic conductivity (ft/d),

I is the hydraulic gradient (ft/ft),

n is the effective, or connected, porosity through which water flows (dimensionless).

Table 4.3 shows the starting locations, discharge points, and travel times for groundwater from various locations on SNL/KAFB. A uniform, effective porosity of 0.2 was assumed for all layers. Note that if the porosity were higher, the travel time would be longer. Figure 4.8 shows the particle trajectories. The ultimate discharge points are the KAFB and Ridgecrest well fields, at the northern area of the model. These supply wells have a dramatic regional-scale impact on the potentiometric surface.

Travel times for all particles are in excess of 50 years. The location furthest from the model's northern edge and the supply wells had the lowest travel time (the Chemical Waste Landfill). The location closest to the northern edge had the longest travel time (Technical Area 2). This occurred because the groundwater particle released at the CWL flowed only a short distance in low permeability deposits before entering the ancestral Rio Grande axial channel deposits in which groundwater flows much faster.

The groundwater particle from TA-2 flowed entirely through low permeability deposits associated with the Tijeras Arroyo alluvial fan. These results illustrate some main points of the SWHC conceptual model.

4.4 Sources of Error and Model Limitations

A model is an approximation of a real-world system. Simplifications are inherent in the construction of a model and may result in application limitations.

The use of specified-flow boundaries representing connection to the north and south of the ABM is another potential source of error. Since the ABM steady-state model was not recalibrated with the revised aquifer properties at SNL/KAFB and the simulation rerun in its entirety, the possibility exists for some inconsistency between flows and aquifer properties. However, the model was able to be calibrated while reasonably honoring site-specific geologic and hydraulic test data, which implies that any inconsistency is minor. Insufficient water-level data exists to make a more detailed assessment of this potential problem. Since the model matches the data reasonably well, any error associated with these boundaries would result in misspecification of model parameters rather than a change in results and conclusions.

ASTM Standard Guide D5611-94 "Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application" describes several types of sensitivity, and in their terminology, the sensitivity of the specified-flow boundaries would be termed a Type I or Type II sensitivity. In a Type I sensitivity, variation of an input causes insignificant changes in model calibration and conclusions drawn from the model. The sensitivity analysis described in section 4.2.4 shows that the model is sensitive to these boundary flows. Thus a Type II sensitivity, when variation of an input parameter causes significant changes in model calibration but insignificant changes in conclusions drawn from the model, is attached to the specified-flow boundaries. If, for instance, flow through the northern boundary was really 50 percent higher, it is probable that the model would not be calibrated, voiding any conclusions until its recalibration, which, if it met the established calibration goals, would show the same features observed in this calibration. Thus the conclusions would remain unchanged. If the model showed little sensitivity to such flow, the conclusions would also remain unchanged.

Another assumption was the assignment of water pumped from the production wells to discrete model layers. Production wells in the Albuquerque Basin may be screened over long portions of the aquifer, with no attempt to isolate productive intervals. Thus, flow into the wells would come from many poorly defined intervals. A common method of allocating pumpage among multiple layers is to apportion the flow based upon transmissivity of each layer. Thorn et al. (1993) allocated flow to each model layer based upon the proportion of the screen in a layer to the total screen length. The effects of incorrect production well extraction of water from a layer would be to affect estimated hydraulic conductivity and leakance. If, for instance, too large a flow was allocated to a layer, a compensating error in the form of increased hydraulic conductivity would be the result. Over the scale of the basin and the level of detail of the model, any error introduced by pumping misspecification is probably minor, and, in any event, insufficient data exists to quantify this error. A Type I sensitivity is probably associated with this aspect of the model.

Some subtle aspects of the conceptual model cannot be tested, except in an exclusionary sense. For instance, mappings of the USF suggest axial channel deposits are present in the southwest part of the CWL. There is a strong contrast in hydraulic gradient across the area, which also suggests a strong contrast in hydraulic properties. The uppermost water-bearing unit in alluvial facies south of Tijeras Arroyo consists of up to 50 ft of silty clay. Below this interval is an interval of approximately 85 ft that includes several sand layers, each about 10 to 15 ft thick. In the TA-III/V area there are monitoring wells completed in one of the underlying sand units. This hydraulic conductivity of these units is 100 to 1,000 times higher, and the hydraulic head is lower than the head in the overlying fine-grained unit. At the CWL, monitoring wells completed in a deeper sand interval and separated by a horizontal distance of up to 300 ft responded together during a pumping test. This indicates that the sand intervals are relatively continuous at the scale of the CWL and may be connected to the fluvial deposits to the west, which would allow preferentially more flow through these units. Introduction of a higher hydraulic conductivity material in the southwestern and south central area of the CWL, which before this change were over 30 ft too high, was able to bring simulated heads into reasonable agreement. Thus, it appears that some kind of higher hydraulic conductivity sediments are an important feature in this area, but it is not possible to say whether they are fluvial or alluvial.

One issue is whether the faults on SNL/KAFB are low- or high-permeability features. Available data do not strongly support either interpretation. Haneberg (1995) reported on modeling results that he suggested were indicative that these faults are low-permeability features. However, the generic aquifer system Haneberg considered was for confined aquifers with head differences across faults being piezometric, rather than elevational (free surface) heads. While the SNL/KAFB-area aquifers do behave as though they are confined, most often free water is present in the aquifer materials at the height of the peizometric surface, suggesting that the aquifers are only partially confined. Sensitivity analysis showed that, at least with the current representation, the conceptual model is not sensitive to the faults. Part of the difficulty is that the faults are represented by 1 to 3 blocks of lower hydraulic conductivity material embedded in an area where hydraulic conductivity is an order of magnitude or more greater. Because of averaging of properties between blocks (see McDonald and Harbaugh 1988) to compute effective interblock parameters, a single low permeability block does not have the full effect. It might be more appropriate to use the horizontal flow barrier package (Hsieh and Freckleton 1993) to represent the faults as line features.

Since the model boundary flows are derived from the ABM, their use for any long term forecasts must be considered carefully, since the boundary flows will largely control the draw down and flow pattern within the SNL/KAFB. The primary purpose of the SNL/KAFB model was to explore and test various conceptualizations of the area and not act as a long-term predictive tool. It would be better for long term predictions to rely on the ABM after it has been updated and recalibrated to include the new information collected in the SNL/KAFB area.

4.5 Monte Carlo Analysis

In trial-and-error and automated solutions of the inverse problem, discrete sensitivity analysis is used to analyze uncertainty in the solution due to incomplete data. The framework of stochastic analysis was developed to address the role of natural variability and its influence on subsurface processes. In this approach, the heterogeneity is represented in terms of random hydraulic parameters characterized by a limited number of statistical parameters. These random parameters are then input to the classical equations that describe groundwater flow. The resulting predictions are then represented by probability distributions or in terms of statistical moments (i.e., mean and variance). Analytical stochastic solutions exist for simple system configurations, but the complex heterogeneity often encountered in reality requires numerical methods.

There are several methods that can be used to perform such an analysis, including the Monte Carlo, first order uncertainty analysis, and response surface analysis (Peck et al. 1988). Peck et al. (1988) indicate that the Monte Carlo method is possibly the most powerful method available for uncertainty analysis because it requires fewer assumptions than other methods. The modification of MODFLOW by Ruskauff (1994) for Monte Carlo analysis was used. The model input parameters are varied according to preselected probability distributions (or geostatistically simulated spatial distributions) and use the numerical model (MODFLOW) to propagate this variability or heterogeneity into variation in the results using the groundwater flow model as the transfer function. Each new sampling of the input variables is called a realization, and is a single simulation performed with a deterministic model using a particular set of input values. The essentially infinite set of possible variations is called the ensemble. The variability of the results can be analyzed to assess the likelihood of the event of interest occurring.

Zimmerman et al. (1991) proposed a slightly altered form of Monte Carlo simulation in which certain runs were selectively excluded from the analysis. The simulations in which model-predicted head compared poorly with observed head were excluded. The term post-conditioning has been coined to describe this process. The rationale for this exclusion was that the poor match resulted from unrealistic transmissivity realizations inconsistent with the conceptual model. The basis for comparison was a simple hand-calibrated model. Deutsch and Journel (1993) also describe a similar procedure. They state that selecting realizations based on some data not initially input to the model (e.g., a known range in travel time between two points) amount to further conditioning by additional unused information. The realizations selected in this manner are better conditioned to actual data and are better models of the phenomenon being analyzed.

The approach used here embodies the notion, as described above, that a given realization must have some reasonable agreement with reality. Unlike the above approaches, all realizations were kept, but the reasons for poor agreement (or improved calibration) were examined to gain insight into uncertainty in the conceptual model.

A difficulty with the Monte Carlo procedure is determining how many realizations to generate, which is not a trivial consideration for transient simulations as large as the SWHC model. Clifton and Neuman (1982) found that about 300 realizations were sufficient to establish a reasonable level of uncertainty. Jacobson et al. (1985) found that 100 realizations were insufficient to characterize variability. Nichols and Freshley (1993) generated 50 to 70 realizations of a one-dimensional unsaturated flow and transport model to investigate the contribution to travel-time uncertainty from several variables. A total of 50 realizations were generated of the SWHC model. Following the approach of Nichols and Freshley (1993), the purpose of this analysis was more reconnaissance than rigorous determination of statistical fluctuation, and in any case even 50 realizations produced large amounts (>900 MB) of output to be analyzed.

The realizations were generated by drawing samples from the parameters shown in Table 4.4. The parameters to be uncertain were selected based on the sensitivity analysis (see Table 4.2) and availability of data. Ancestral Rio Grande deposits, for instance, in the layers 6 and lower were sensitive, but no data exist as to their properties, thus they were not included. Initial heads were very sensitive but were not included because they are not part of the conceptual model. The sampled value of the parameter was applied to all locations in the model that corresponded to the property of interest (see Ruskauff [1994] for a discussion on sampling strategies). For instance, in sampling ancestral Rio Grande axial channel deposits, a value is drawn from the distribution and then inserted into the model in all places where those deposits occur. The choice of distribution type, range, and variability should ideally be made from statistical analysis from data in the area of interest. However, even the characterization performed by the SWHC Project does not provide sufficient data to perform such an analysis. Typically it is assumed (often with little justification) that hydraulic conductivity is lognormally distributed, with a characteristic tail of high values and with zero an inadmissible value. Young et al. (1991) evaluated the univariate distribution of hydraulic conductivity at a site and concluded that the hypothesis of lognormality could not be theoretically justified. They also concluded that from a practical standpoint, assuming lognormality was reasonable, but the standard assumption of lognormality for hydraulic conductivity should be evaluated on a site-specific basis and with regard to the project objectives.

The objectives of the Monte Carlo analysis were to examine model uncertainty and the interactions between parameters. In this sense, simple distributions are easier to justify. Also, normal distributions will tend to produce values clustered around the mean, which, if the distribution were actually known, would be reasonable, with the occasional extreme value providing unusual results. Ruskauff (1996) performed a univariate statistical and geostatistical analysis on the basin pumping test data summarized by Thorn et al. (1993) and found that multiple, nonlognormal distributions existed. If anything, the individual distributions may be characterized as normal. Woodbury et al. (1995) investigated the effects of assuming the distribution in stochastic analysis. They used an expression based on the uniform distribution and Gaussian distribution to analyze outcomes of draw down from a pumping well. The results of sampling from a uniform distribution had considerably more spread than the results from a Gaussian distribution, because the Gaussian distribution will draw more values near the mean than from the extremes. They point out that it is possible to obtain bounding estimates of parameters that are used directly in a uniform distribution, but it may be difficult to obtain enough data to assign a site-specific distribution. For these reasons, simple, uniform distributions were used for all variables. The bounds for Rio Grande axial channel and Rio Grande flood plain deposits were established from the 95 percent confidence interval from inverse parameter estimation. The others were set within ranges deemed to be reasonable from SWHC Project data.

The basis for examining realizations was the SS, normalized by the calibrated model value. Figure 4.9 shows the normalized SS as a function of realization. An interesting feature of this plot is the apparent plateau of normalized SS below 1.0, which suggests some limiting value of a sensitive parameter has been reached. Figures 4.10 to 4.14 show normalized SS plotted against sampled parameter value. Most of the plots suggest little relationship between normalized SS and the sampled parameter value, which indicates relative insensitivity. In Figure 4.10, for instance, both low and high values of normalized SS occur over the entire range sampled. Specific yield (Figure 4.13) shows a distinct correlation between normalized SS and sampled value. Values lower than the calibrated 0.15 cause a deterioration in fit; values greater improve it to a certain extent. Beyond values much above 0.16, model fit is not improved with increasing specific yield. Values decreasing from 0.15 steadily degrade model fit. The number of points for which normalized SS is greater than 1 (specific yield less than 0.15) in Figure 4.13 is the same as in the other figures, confirming what the sensitivity analysis suggested, that specific yield is a very sensitive parameter in the model. The scattering of results for alluvial fan hydraulic conductivity and leakance is somewhat greater than for the other parameters, thus they are influencing the results to some extent (as suggested by the sensitivity analysis).

The improvement of model fit with increasing specific yield is consistent with the fact that the model has a bias towards underprediction (too dry). Increasing specific yield allows more flow from storage to buffer the decline in heads. If a similar analysis were performed on the SWHC conceptual model with USGS recharge, the reverse would be true since that model has an overpredictive (too wet) bias. It is significant that only about a 7 percent change in specific yield has such a large impact on model results since specific yield is not known with this level of accuracy. Indeed, no specific yield data is available for the basin, and a generally plausible range of values is 0.1 to 0.25 (Johnson, 1967) for sediments such as the SFG.

Table 4.1. Calibration Criteria and Achieved Values

Criteria	Goal	Baseline USGS Model	SWHC CM, USGS Tijeras Arroyo Flow	SWHC CM, SWCH Tijeras Arroyo Flow
Mean error, ME (ft)	9.4	-7.6	-2.91	4.23
Error standard deviation, SD (ft)	9.4	9.65	6.31	6.35
Ratio of SD to total observed head change	10%	10.2 %	6.7 %	6.7 %
Sum of errors squared, SS (ft^2)	110,000	230,000	74,400	89,800

Table 4.2. Calibrated Model Sensitivity Coefficients

Parameter	Base Value	Perturbed Value	SS (ft^2)	Sensitivity(ft^2)
Tijeras Arroyo Recharge	2.2×10^6 ft^3/yr	22×10^6 ft^3/yr	78300	1311
K252[a], Rio Grande Axial Deposits Layers 1-5	210 ft/d	150 ft/d	90700	2100
K4, Alluvial Fan, Layers 1-5	5 ft/d	10 ft/d	77600	12500
K2, Alluvial Fan, Layers 1-2	0.01 ft/d	0.1 ft/d	89700	44
K130, Transitional, Layers 1-5	40 ft/d	15 ft/d	94000	6240
T711[b], Layer 11	2000 ft^2/d	3000 ft^2/d	98	1600
T1255, Layer 10	12000 ft^2/d	10000 ft^2/d	91100	3000
T1291, Layer 9	37500 ft^2/d	50000 ft^2/d	89600	1500
T1290, Layer 8	30000 ft^2/d	40000 ft^2/d	89300	2400
T1289, Layer 7	22500 ft^2/d	30000 ft^2/d	89400	2100
T1268, Layer 6	15000 ft^2/d	20000 ft^2/d	89700	1200
T32, Fault in layers 1-5	3.0 ft/d	0.3 ft/d	89800	333
Initial Head	Median = 4918.7	+10 ft	72800	8.5×10^6
K239, Layer 3-4 Rio Grande alluvium	40	60	86200	7800
L2660[c], Layers 2-4	2.663×10^{-4}	8×10^{-5}	127000	52745
L3781, Layers 2-3	0.01	0.005	89800	600
L4386, Layers 2-3	5.8×10^{-3}	0.001	88900	1450
L57, Layer 10	4.4445×10^{-5}	1×10^{-4}	89400	560
L1270, Layer 9	4.6154×10^{-4}	1×10^{-3}	91200	943
L2088, Layer 8	6.6667×10^{-4}	1×10^{-3}	90300	400
L2252, Layer 7	8.5715×10^{-4}	3×10^{-3}	92000	760
L2455, Layer 6	1.2×10^{-3}	0.05	93100	78
L2847, Layer 5	1.8265×10^{-3}	0.05	89800	11
Specific Storage (S_S), Layers 1-5	$2 \times 10\text{-}6$ ft^{-1}	$3 \times 10\text{-}6$ ft^{-1}	89500	1200
Specific Storage (S_S), Layers 6-11	$2 \times 10\text{-}6$ ft^{-1}	$3 \times 10\text{-}6$ ft^{-1}	84500	11200
Specific Yield (S_y)	0.15	0.25	167000	115350

[a] K denotes hydraulic conductivity zone
[b] T denotes transmissivity zone
[c] L denotes leakance zone

Table 4.3 Groundwater Travel Times and Discharge Locations for Various Locations on SNL/KAFB

Starting Location	Final Location	Travel Time (years)
Technical Area 2	KAFB-5	73
Chemical Waste Landfill	Ridgecrest 5	54
Mixed Waste Landfill	Ridgecrest 3	64
LWDS	Ridgecrest 3	70

Table 4.4 Monte-Carlo Analysis Input Parameters

Parameter	Distribution Type	Limits
K4 Alluvial Fan	Uniform	1-10 ft/d
K130 Rio Grande floodplain	Uniform	5-75 ft/d*
K252 Rio Grande axial channel deposits	Uniform	138-280 ft/d*
L2660 Alluvial Fan Leakance	Uniform	8×10^{-4} - 8×10^{-5} d^{-1}
S_y Specific Yield layers 1-5	Uniform	0.1 - 0.2

* 95 percent confidence limits from parameter estimation

5.0 DISCUSSION AND CONCLUSIONS

The conceptual model of the hydrogeology of SNL/KAFB developed by SWHC was the basis for the numerical model. The major points of the conceptual model are summarized as follows:

- Channel deposits of the ancestral Rio Grande extend through the west SNL/KAFB area in a north-south direction.
- Alluvial fan deposits extend from the east into the ancestral Rio Grande deposits.
- Sharp contrasts in hydraulic properties occur as a result of the abutment of lithologies deposited in distinctly different environments.
- Recharge occurs mainly from Tijeras Arroyo, Arroyo del Coyote, and the Manzano Mountains mountain front, with some component of flow from the bedrock.
- Sediments decrease in hydraulic conductivity with depth as the USF grades into the MSF and LSF, which were deposited under different (mainly low-energy alluvial) environments.
- The top of the aquifer is in the USF.
- Large amounts of groundwater flow are from storage release (i.e. dewatering).
- Pumpage greatly exceeds recharge from all sources (precipitation, Rio Grande leakage).
- Fault systems in the SFG probably act as restrictions to groundwater flow, abutting low-flow lithologies and cementation of the fault gouge.

The numerical model of the area near the KAFB was constructed using the USGS MODFLOW model and the ABM as a starting point. Goals for transient calibration were established using standard and accepted techniques. These goals were met during the model calibration process, which allows the model to be used to draw conclusions about the conceptual model at SNL/KAFB.

The modifications made to the USGS ABM included addition of a long, north-south strip of axial channel deposits, extending much further than in the ABM. In addition, SWHC Project estimates of hydraulic conductivity of alluvial fan material along the mountains were much lower than in the ABM, as was recharge from infiltration along Tijeras Arroyo. The ABM recharge along Tijeras Arroyo is over an order of magnitude higher than that estimated by the SWHC Project. Two models were calibrated to bracket the conceptual uncertainty caused by this difference. In the first, the recharge rate specified by the USGS was maintained and the model modified to reflect the SNL/KAFB conceptual model. For the second model, recharge along Tijeras Arroyo was reduced to the value estimated by the SWHC Project. The high recharge case required high hydraulic conductivities in the alluvial fan material where Tijeras Arroyo enters SNL/KAFB. The values were not unreasonable when compared with SWHC data from

Technical Area 2, but the model still exhibited a pronounced overprediction (too much water) in the area, which suggested that the Tijeras Arroyo flow rate in the ABM may be too high. In the low recharge case, hydraulic conductivities in the area where Tijeras Arroyo enters SNL/KAFB were very low.

The SWHC Project model differs from the ABM in several ways, and to some extent these differences reflect both additional data and a different approach taken between the USGS and SNL/NM. The USGS did not attempt to calibrate the ABM, rather the best conceptual representation was independently determined and then areas where significant deviation occurred were identified. The identified area did not include SNL/KAFB. One of the benefits of calibration (particularly automated methods) is that hypotheses can be tested. Thus for the SNL/KAFB model areas of significant model deviation were not left for future resolution. Resolution was attempted, and then the required adjustments examined to see how (if at all) they related to the conceptual model. One example of the difference in approach is in the area near the southwest corner of the CWL, where thin sheets of high hydraulic conductivity sand embedded in otherwise low hydraulic conductivity deposits and connected to axial channel deposits were thought to be "thief" zones. The model was unable to replicate the observed flow conditions until hydraulic conductivity in the area was raised to include the effects of these sands. Since an independent prediction was not attempted the model is not verified (Anderson and Woessner, 1992).

Travel times for all particles are in excess of 50 years. The location furthest from the model's northern edge and the supply wells had the lowest travel time (the Chemical Waste Landfill). The location closest to the northern edge had the longest travel time (Technical Area 2). This occurred because the groundwater particle released at the CWL flowed only a short distance in low permeability deposits before entering the ancestral Rio Grande axial channel deposits in which groundwater flows much faster. The groundwater from TA-2 flowed entirely through low permeability deposits associated with the Tijeras Arroyo alluvial fan. These results illustrate some main points of the SWHC conceptual model.

Deterministic and Monte Carlo sensitivity analyses were performed to examine the importance of various aspects of the conceptual model. Specific yield and specific storativity were sensitive parameters, which confirms the conceptual model that has large amounts of flow from storage (i.e. dewatering the basin) as a source of water pumped from the SFG. Initial conditions were extremely sensitive (which is correct since this a transient problem). Comparison of SWHC Project pumping tests with the assumed value of specific storage suggests that it is reasonable. However, the model is more sensitive to specific yield than specific storage (which is reasonable since more water is released from storage per unit decline of the potentiometric surface under water table than confined conditions), which is not well characterized on SNL/KAFB or in the basin in general. This situation has the potential to create large compensating errors, since both hydraulic conductivity and specific yield can be balanced for a given model boundary flux to yield the same rate of decline. It is unlikely, given these uncertainties, that much predictive power can be associated with any model of the basin. However, for the purpose of this analysis, a comparative use of the model is still reasonable.

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6.0 REFERENCES

Anderholm, S.K., and T.F. Bullard, 1987, Description of piezometer nests and water levels in the Rio Grande valley near Albuquerque, Bernalillo County, New Mexico: U.S. Geological Survey Open-File Report 87-122, 51 p.

Andersen, P., 1993, *A Manual of Instructional Problems for the U.S.G.S. MODFLOW Model*, EPA/600/R-93/010, RSKERL, Ada, OK.

Anderson, M.P. and W.W. Woessner, 1992, *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, Academic Press, Inc., New York.

Bjorklund, L.J., and B.W. Maxwell, 1961, Availability of ground water in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer Technical Report 21, 117 p.

deMarsily, G., 1986, *Quantitative Hydrogeology*, Academic Press, San Diego, CA.

Deutsch, C. and A. Journel, 1993, *GSLIB Geostatistical Software Library and User's Guide*, Oxford University Press, New York, 340 p.

Environmental Simulations, Inc., 1996, *Guide to Using Groundwater Vistas*.

Freeze, G.A. and M. Reeves, 1996, "A deterministic sensitivity analysis method to aid conceptual model development," *Calibration and Reliability in Groundwater Modeling*, K. Kovar and P. van der Heijde, eds., IAHS Publication No. 237.

Gelhar, L., 1986, "Stochastic subsurface hydrology from theory to applications," *Water Resources Research*, (Supplement), v. 22, no. 9, pp. 135S-145S.

GMI (Groundwater Management Incorporated), 1988a, Pumping Test Data Analysis: Burton Well Field, City of Albuquerque, New Mexico, unpublished report prepared for Black & Veatch Entineers, Aurora, CO, February 2, 1988.

GMI (Groundwater Management Incorporated), 1988b, Pumping Test Data Analysis: Miles Road Well Field, City of Albuquerque, New Mexico, unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

GMI (Groundwater Management Incorporated), 1988c, Pumping Test Data Analysis: Ridgecrest Well Field, City of Albuquerque, New Mexico, unpublished report prepared for Black & Veatch Engineers, Aurora, CO, February 2, 1988.

Haneberg, W.C., 1995, "Steady state groundwater flow across idealized faults," *Water Resources Research*, Vol. 31, No. 7, pp. 1815-1820, July 1995.

Hawley, J.W., and C.S. Hasse, eds., 1992, Hydrogeologic framework of the Northern Albuquerque Basin, New Mexico Bureau of Mines and Mineral Resources Open-File Report 387.

Hawley, J.W. and T.M. Whitworth, 1996, Hydrogeology of potential recharge areas for the basin- and valley-fill aquifer systems, and hydrogeochemical modeling of proposed artificial recharge of the Upper Santa Fe Aquifer, Northern Albuquerque Basin, New Mexico, New Mexico Bureau of Mines and Mineral Resources Open-File Report 402-D.

Haywood, C.E., 1992, Isostatic residual gravity anomalies of New Mexico, U.S. Geological Survey Water-Resources Investigations Report 91-4065, 27 p.

Hill, M.C., 1992, A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional groundwater flow model using nonlinear regression, U.S. Geological Survey Open-File Report 91-484.

Hsieh, P.A. and J.R. Freckleton, Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, U.S. Geological Survey Open-File Report 92-477, Sacramento, California.

Hudson, J.D., 1982, Water-level map of the San Jose well field and vicinity, Albuquerque, New Mexico, Spring 1981, U.S. Geological Survey Open-File Report 82-375, 2 p.

Jacobsen, E., M. Freshley, and H. Dove, 1985, *Investigations of Sensitivity and Uncertainty in Some Hydrologic Models of Yucca Mountain and Vicinity*, SAND84-7212, Sandia National Laboratories, Albuquerque, New Mexico.

Johnson, A.I., 1967. Specific yield-compilation of specific yields for various materials; U.S. Geological Survey Water-Supply Paper 1662-D.

Kaehler, C.A., 1990, Lithology of basin-fill deposits in the Albuquerque-Belen Basin, New Mexico, U.S. Geological Survey Water-Resources Investigations Report 89-4162,14 p.

Kelly, T.E., 1982, "History of water use in the greater Albuquerque area," Guidebook to Albuquerque Country II: New Mexico Geological Society, 33d Field Conference, J.A. Grambling and S.G. Wells, eds., p. 351-356.

Kelley, V.C., 1977, Geology of Albuquerque Basin, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Memoir 33, 60 p.

Kernodle, J.M. and W.B. Scott, W.B., 1986, Three-dimensional model simulation of steady-state ground-water flow in the Albuquerque-Belen Basin, New Mexico, U.S. Geological Survey water-Resources Investigations Report 84-4353, 58 p.

Kernodle, J.M., R.S. Miller, and W.B. Scott, 1987, Three-dimensional model simulation of transient ground-water flow in the Albuquerque-Belen Basin, New Mexico, U.S. Geological Survey Water-Resources Investigations Report 86-4194, 86 p.

Kernodle, J.M., D.P. McAda, and C.R. Thorn, 1995, Simulation of ground-water flow in the Albuquerque Basin, Central New Mexico, 1901-1994, with projections to 2020, U.S. Geological Survey, Water-Resources Investigations Report 94-4251.

Kues, G.E., 1986, Ground-water levels and direction of ground-water flow in the central part ofBernalillo County, New Mexico, Summer 1983, U.S. Geological Survey Water-Resources Investigations Report, 24 p.

Kues, G.E., 1987, Ground-water level data for the Albuquerque-Belen Basin, New Mexico, through water year 1985, U.S. Geological Survey Open-File Report 87-116, 51 p.

Lambert, P.W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico: Albuquerque, University of New Mexico Ph.D. dissertation, 329 p.

Lozinsky, R.P., 1988, Stratigraphy, sedimentology, and sand petrology of the Santa Fe Group and pre-Santa Fe Tertiary deposits in the Albuquerque Basin, central New Mexico: Socorro, New Mexico Institute of Mining and Technology, Ph.D. dissertation.

Mack, G.H. and W.R. Seager, 1990, Tectonic control on facies distribution of the Camp Rice and Palomas Formations (Pliocene-Pleistocene) in the southern Rio Grande rift, Geological Society of America Bulletin, v. 102, p. 45-53.

McDonald, M. and A. Harbaugh, 1988, A modular three-dimensional finite-difference ground water flow model, Techniques of Water-Resources Investigations 06-A1, U.S. Geological Survey, Reston, VA.

National Research Council, 1990, *Ground-Water Models, Scientific and Regulatory Applications*, National Academy Press, Washington, D.C.

Nichols, W. and M. Freshley, 1993, "Uncertainty Analyses of Unsaturated Zone Travel Time at Yucca Mountain," *Groundwater*, v. 31, no. 2, pp. 293-302.

Olsthoorn, T.N. and P.T.W.J. Kamps, 1996, "Groundwater model calibration for the Amsterdam Water Supply dune area," *Calibration and Reliability in Groundwater Modeling,* K. Kovar and P. van der Heijde, eds., IAHS Publication No. 237.

Peck, A., S. Gorelick, G. deMarsily, S. Foster, and V. Kovalevsky, 1988, *Consequences of Spatial Variability in Aquifer Properties and Data Limitations for Groundwater Modeling Practice*, IAHS Publication No. 175, Washington, D.C.

Poeter, E.P. and M.C. Hill, 1996, "Unrealistic parameter estimates in inverse modeling: a problem or benefit for model calibration," *Calibration and Reliability in Groundwater Modeling*, K.Kovar and P. van der Heide, eds., ModelCARE '96, IAHS Pub. No. 237.

Pollock, D., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model, U.S. Geological Survey Open File Report 89-381, Reston, VA.

Reeder, H.O., L.J. Bjorkland, and G.A. Dinwiddie, 1967, Quantitative analysis of water resources in the Albuquerque area, New Mexico–Computed effects on the Rio Grande of pumpage of ground water, 1960-2000, New Mexico State Engineer Technical Report 33.

Rumbaugh, J.O. and L.L. Ruskauff, 1993, Geraghty & Miller Modeling Survey, Analysis of May 1992 Survey Results, Geraghty & Miller Modeling Group, Reston, Virginia.

Ruskauff, G.J., 1994, "A Methodology for Performing Monte Carlo Analysis with MODFLOW and MODPATH," Proceedings of the 1994 Groundwater Modeling Conference, J.W. Warner and P. van der Heijde, eds., Fort Collins, CO, August 10-12.

Ruskauff, G.J., 1996, "Geostatistical Analysis of the Hydraulic Conductivity of the Upper Santa Fe Group, Albuquerque Basin, New Mexico, Subsurface Fluid-Flow (Ground-Water and Vadose Zone) Modeling," ASTM STP 1288, Joseph D. Ritchey and James O. Rumbaugh, III, eds., American Society of Testing and Materials.

Summers, W.K., 1992, Effects of Albuquerque's pumpage on the Rio Grande and the rate at which Albuquerque will have to release San Juan-Chama water to offset them, City of Albuquerque internal memorandum, variously paged.

SNL/NM, 1993, *Site-Wide Hydrogeologic Characterization Project Calendar Year 1992 Annual Report*, SAND93-0681, Environmental Restoration Program, Sandia National Laboratories, Albuquerque, New Mexico.

SNL/NM, 1994, *Site Wide Hydrogeologic Characterization Project Calendar Year 1993 Annual Report*, Environmental Restoration Program, Sandia National Laboratories, Albuquerque, New Mexico.

SNL/NM, 1995, *Site-Wide Hydrogeologic Characterization Project Calendar Year 1994 Annual Report*, Environmental Restoration Program, Sandia National Laboratories, Albuquerque, New Mexico.

SNL/NM, 1995a, *Chemical Waste Landfill Groundwater Assessment Report*, Environmental Restoration Project, Sandia National Laboratories, Albuquerque, New Mexico.

SNL/NM, 1996, *Site-Wide Hydrogeologic Characterization Project Calendar Year 1995 Annual Report*, Environmental Restoration Program, Sandia National Laboratories, Albuquerque, New Mexico.

Theis, C.V., 1938, "Ground-water in the middle Rio Grande valley," National Resources Committee, Regional Planning part VI-The Rio Grande joint investigation in the upper Rio Grande Basin in Colorado, New Mexico, and Texas, 1936-37: U.S. Government Printing Office, v.1, p. 268-291.

Theis, C.V., and G.C. Taylor, 1939, "Ground-water conditions in the middle Rio Grande valley, New Mexico," New Mexico State Engineer 12th-13th Biennial Reports, 1934-38, p. 263-271.

Thorn, C.R., D.P. McAda, and J.M. Kernodle, 1993, Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, Central New Mexico, U.S. Geological Survey Water-Resources Investigations Report 93-4149, 106 p.

U.S. Army Corps of Engineers, 1979, Albuquerque greater urban area water supply study, U.S. Army Corps of Engineers, Albuquerque District, Hydrologic Engineering Center, 8 sec., 225 p.

U.S. Geologic Survey, 1993, *Installation Restoration Program, Stage 2A*, RI/FS Technical Report for Kirtland Air Force Base, USGS Water Resources Division, Albuquerque, NM.

Watermark Computing, Inc., 1994, *PEST User's Guide*, version 1.08.

Woodbury, A., F. Render, and T. Ulrych, 1995, "Practical Probabilistic Ground-Water Modeling," *Groundwater*, v. 33, no. 4, p. 532.

Young, S.C., J.C. Herweijer, and D.J. Benton, 1991, "Geostatistical evaluation of a three-dimensional hydraulic conductivity field in an alluvial aquifer," Proceedings of the 5th annual Canadian American Conference on Hydrogeology, Calgary, September 18-20, 1990, NWWA, Dublin, Ohio.

Zimmerman, D., Hanson, and P. Davis, 1991, *Parameter Estimation Techniques and Uncertainty in Ground Water Flow Model Prediction*, Sandia National Laboratories, Albuquerque, New Mexico, DOE Publication DE91 000405.

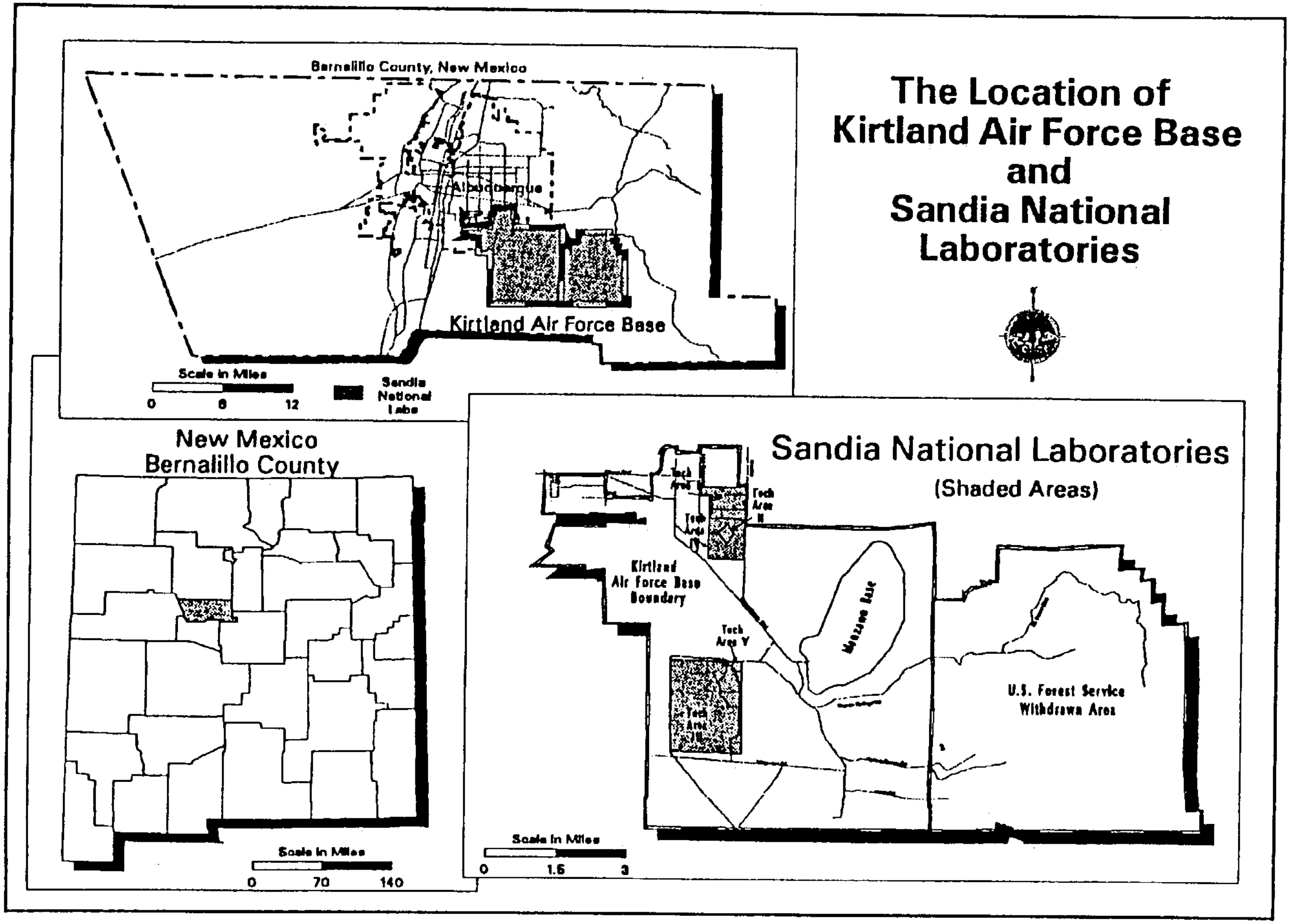


Figure 1.1. Location of Kirtland Air Force Base and Sandia National Laboratories.

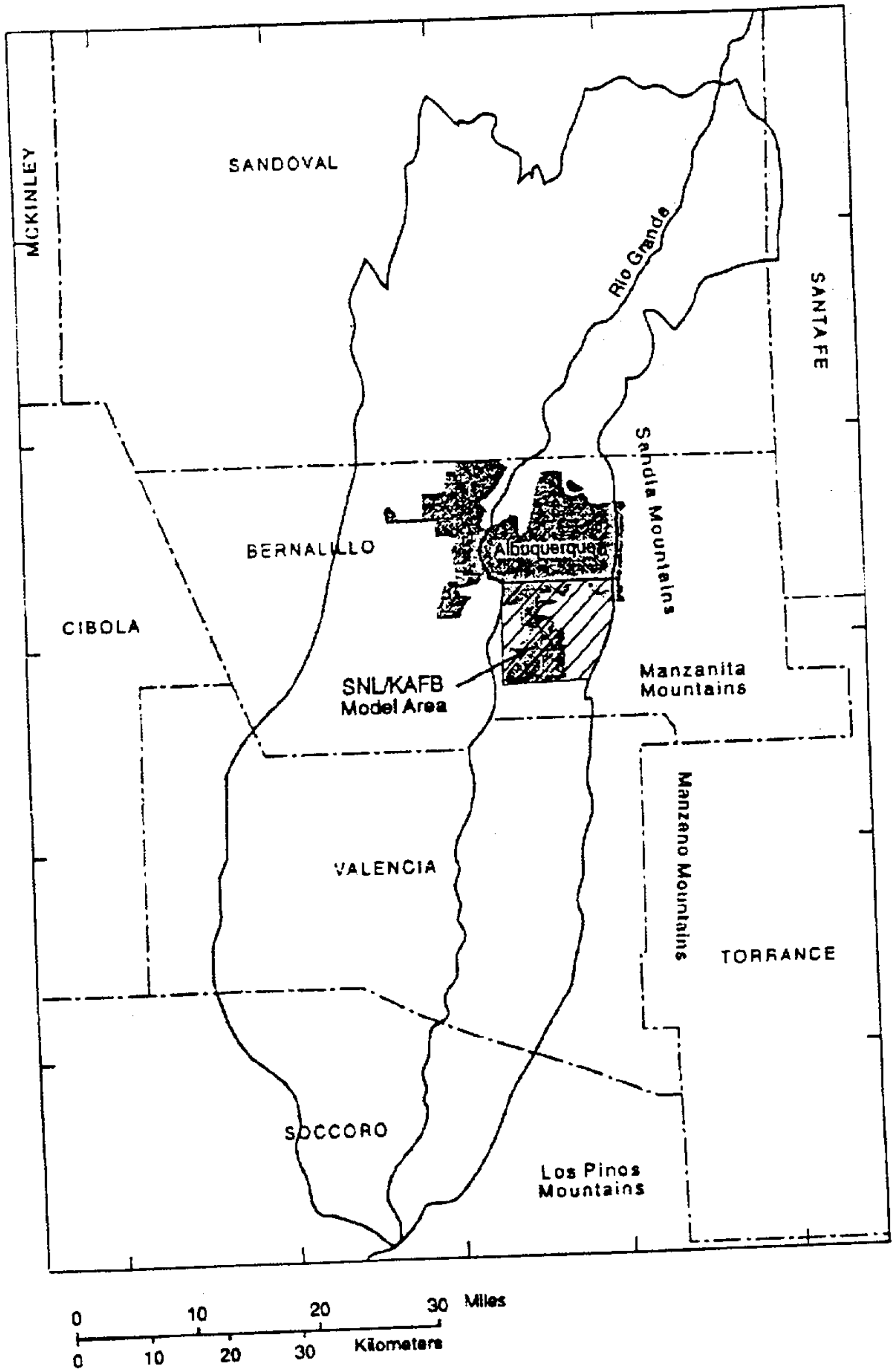


Figure 2.1. Location of the Sandia National Laboratories/Kirtland Air Force Base Model Area in the Albuquerque Basin.

ERA/SYSTEM/SERIES			UNIT/FORMATION		STRAT. COLUMN	DESCRIPTION
CENOZOIC	NEOGENE	Holocene to Middle Pleistocene	Surficial Units			Cross-bedded, fine- to medium-grained eolian sand Poorly-sorted silty sandy cobble to boulder gravel Poorly-sorted silty sandy cobble to boulder gravel with relict and buried soils *Unconformity*
CENOZOIC	NEOGENE	Early Pleistocene to Early Miocene	Santa Fe Group	Upper Santa Fe Unit		Basinal: coarse- to fine-grained sandstone; common buried soils Marginal: pebbles, cobbles in fine-grained matrix
CENOZOIC	NEOGENE	Early Pleistocene to Early Miocene	Santa Fe Group	Middle Santa Fe Unit		Basinal: medium- to fine-grained sandstone and mudstone; common buried soils Marginal; conglomeratic sandstone to pebbles and cobbles; common buried soils
CENOZOIC	NEOGENE	Early Pleistocene to Early Miocene	Santa Fe Group	Lower Santa Fe Unit		Basinal: medium- to fine-grained sandstone, sandy mudstones Marginal: conglomeratic sandstone and mudstone *Unconformity*
CENOZOIC	PALEOGENE	Oligocene	Unit of Isleta #2 Well			Fine- to coarse-grained sandstone; claystone, silt beds; volcanic detritus and ash-flow tuffs
CENOZOIC	PALEOGENE	Eocene to Paleocene	Baca/ Galisteo Formations			Sandstone, variegated mudstone, and conglomerate *Unconformity*
MESOZOIC		Upper Triassic	Santa Rosa Sandstone			Buff brown sandstone, petrified wood
PALEOZOIC		Upper Permian	San Andres Formation			Gray limestone, separated by red shale *Unconformity*
PALEOZOIC		Upper Permian	Glorieta Sandstone			Medium- to coarse-grained yellowish gray sandstone
PALEOZOIC		Lower Permian	Yeso Formation			Upper: gypsiferous sandstone, siltstone, and limestone Lower: fine-grained sandstone and siltstone
PALEOZOIC		Lower Permian	Abo Formation			Fine- to coarse-grained sandstone and conglomerate with interbedded siltstone
PALEOZOIC		Lower Permian	Madera Group	Bursum Fm.		Finely laminated silty mudstone
PALEOZOIC		Upper to Middle Pennsylvanian	Madera Group	Wild Cow Formation		Rhythmically bedded sequence: conglomerate, sandstone, siltstone, shale, and limestone
PALEOZOIC		Upper to Middle Pennsylvanian	Madera Group	Los Moyos Formation		Gray calcarenite with chert
PALEOZOIC		Middle Pennsylvanian	Sandia Formation			Fining-upwards clastic sequence: conglomerate to calcareous siltstone *Unconformity*
PRECAMBRIAN			Isleta Metasediments Tijeras Greenstone Complex Coyote Canyon Sequence Sandia Granite			Phyllite; meta-arkose; metaquartzite; greenstone; metarhyolite; quartzite; microcline and biotite granite

Figure 2.2. Generalized Stratigraphic Column of the Sandia National Laboratories/Kirtland Air Force Base Area.

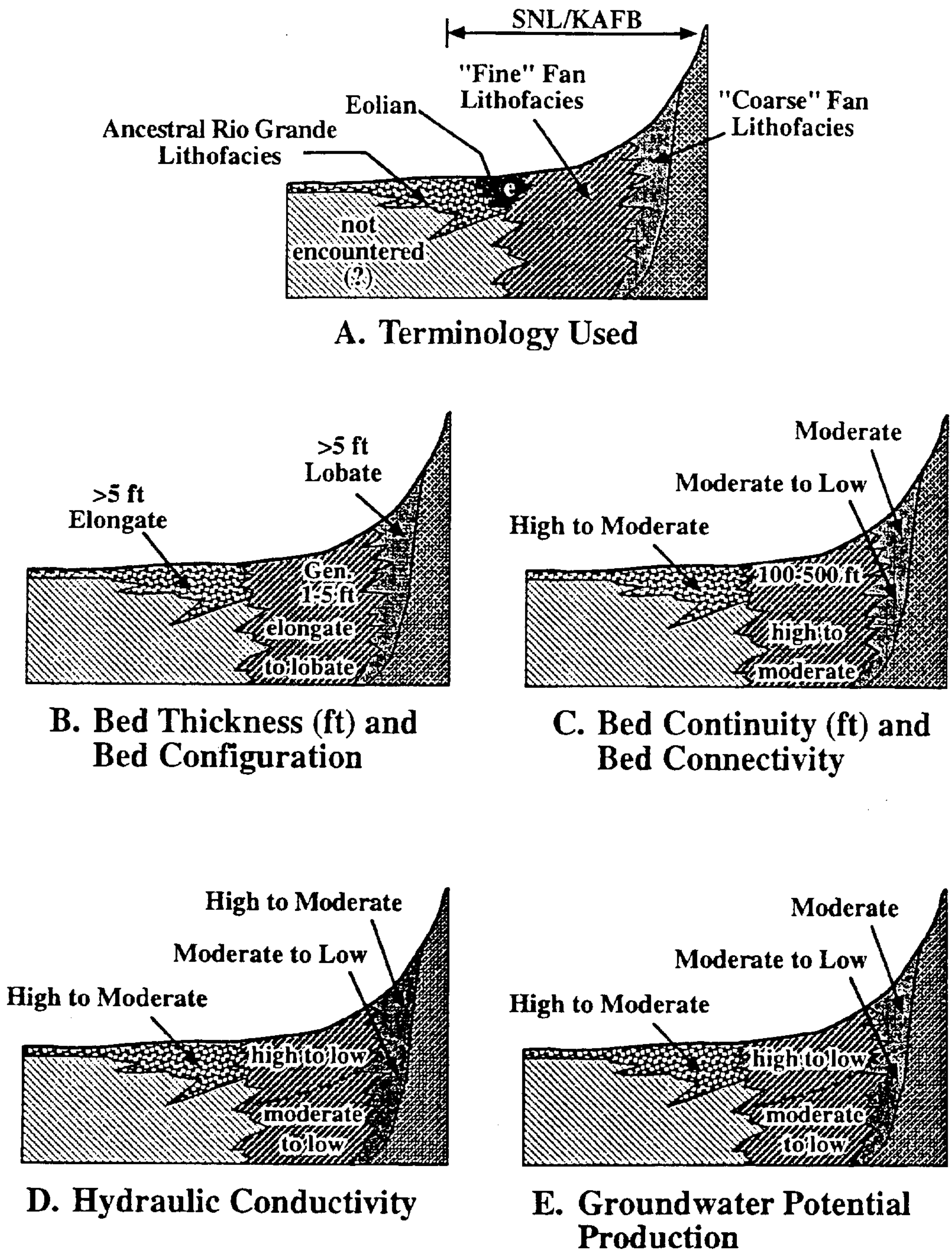


Figure 2.3. Relationship of Santa Fe Group Lithofacies to Hydrogeologic Parameters.

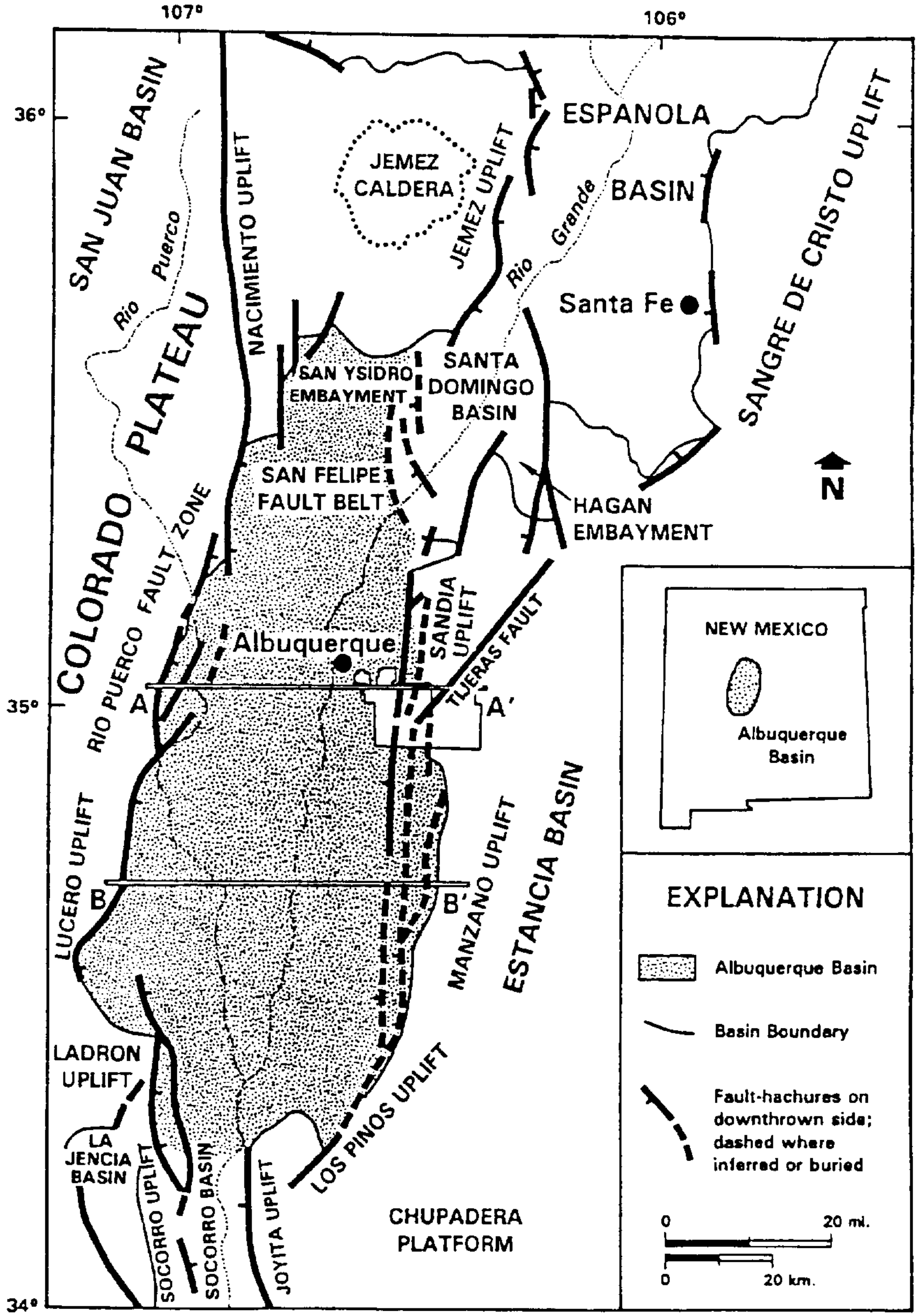


Figure 2.4. Generalized Regional Tectonic Map of the Albuquerque Basin.

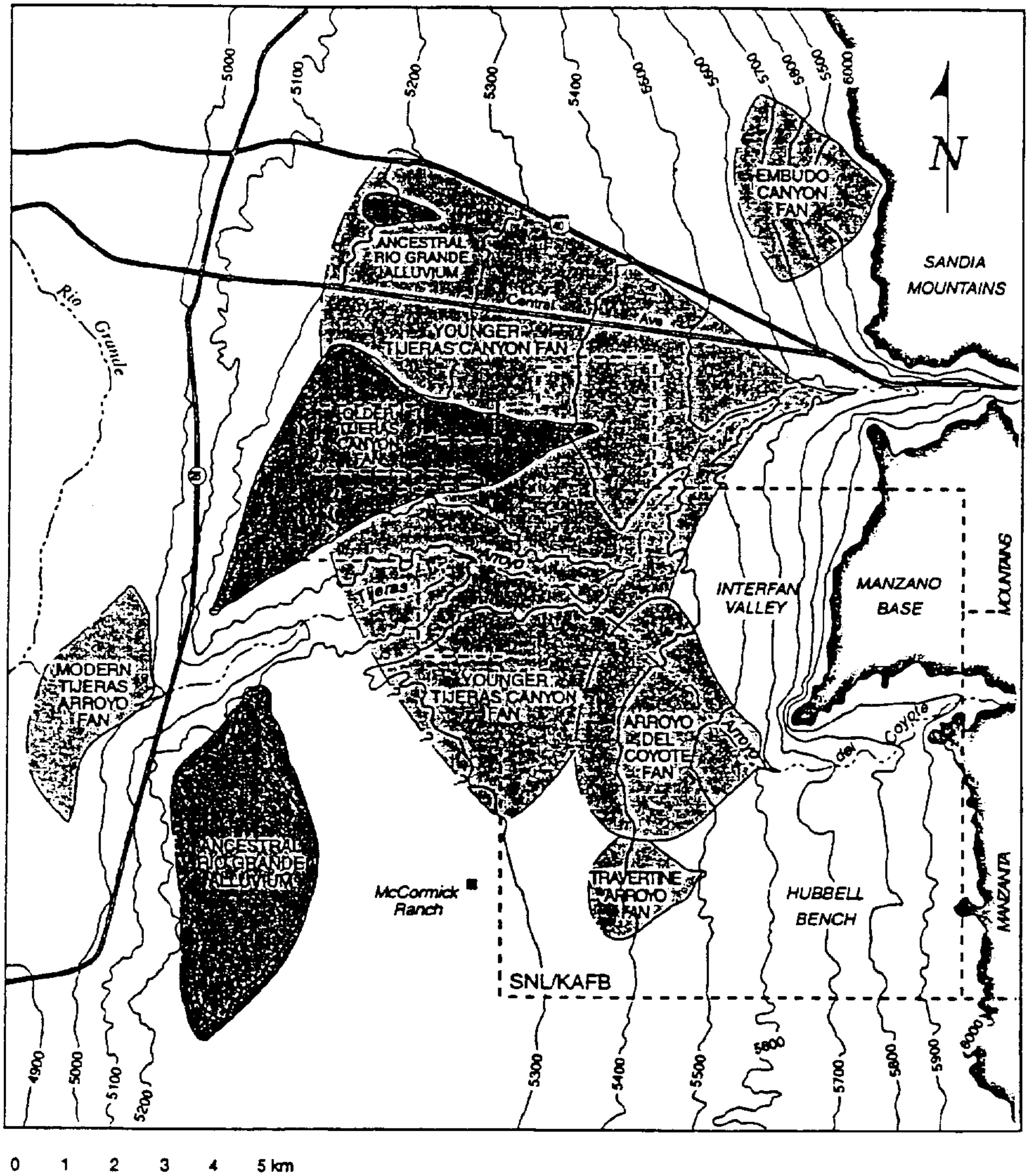


Figure 2.5. Generalized Topographic Map of the Sandia National Laboratories/Kirtland Air Force Base Area West of the Sandia and Manzanita Mountains.

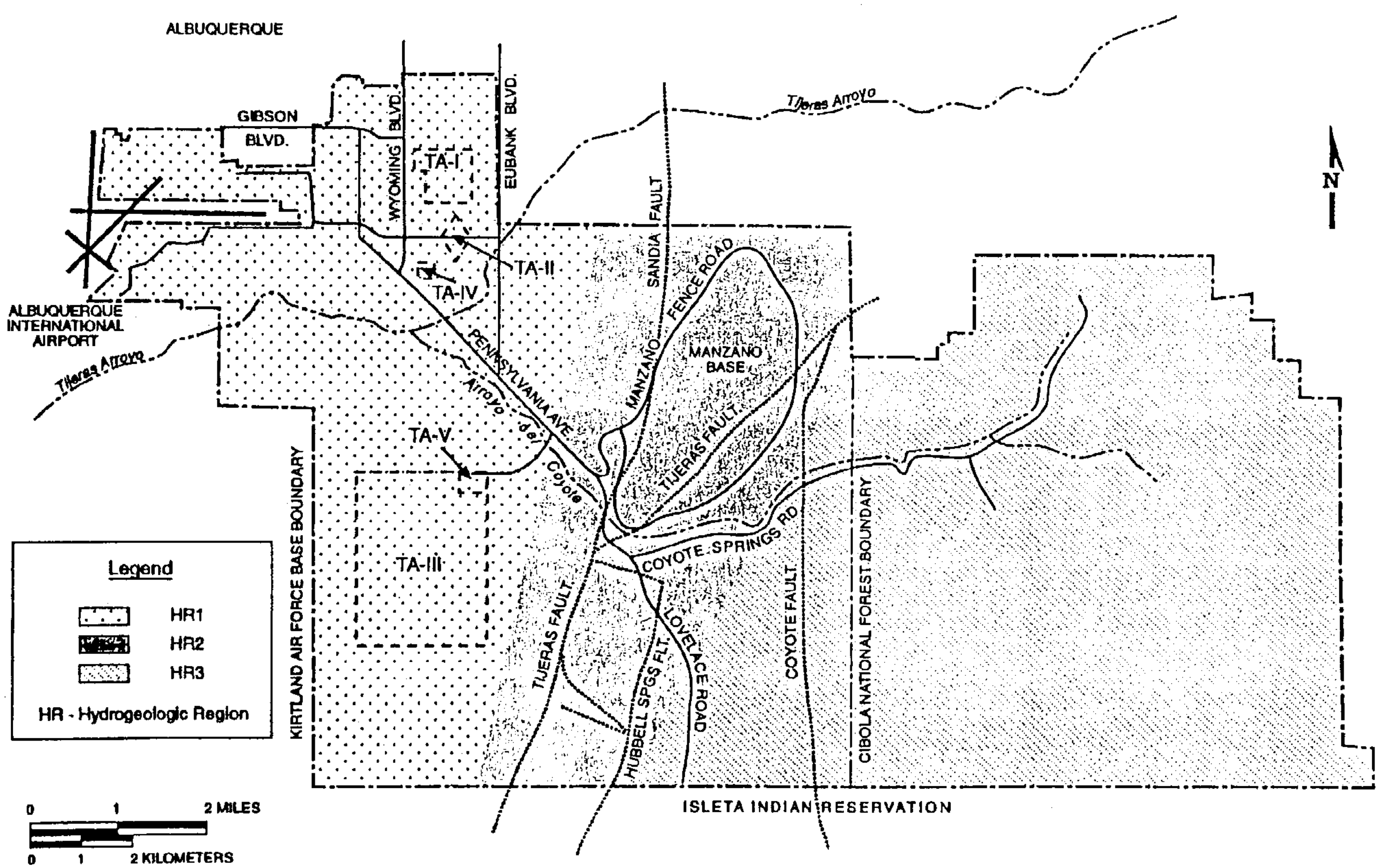


Figure 2.6. Hydrogeologic Regions Identified by Sandia National Laboratories/New Mexico.

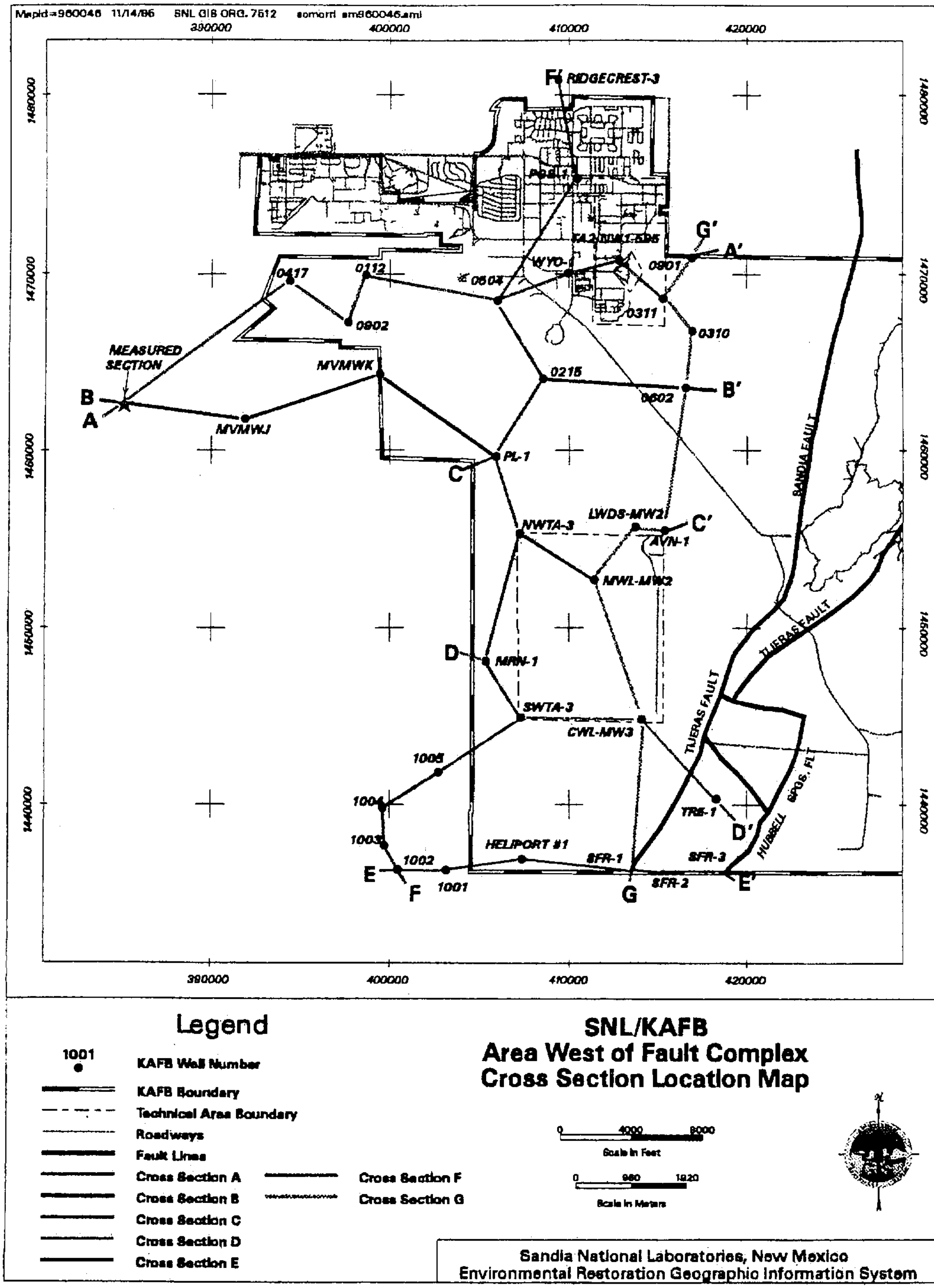


Figure 2.7 Cross Section Location Map.

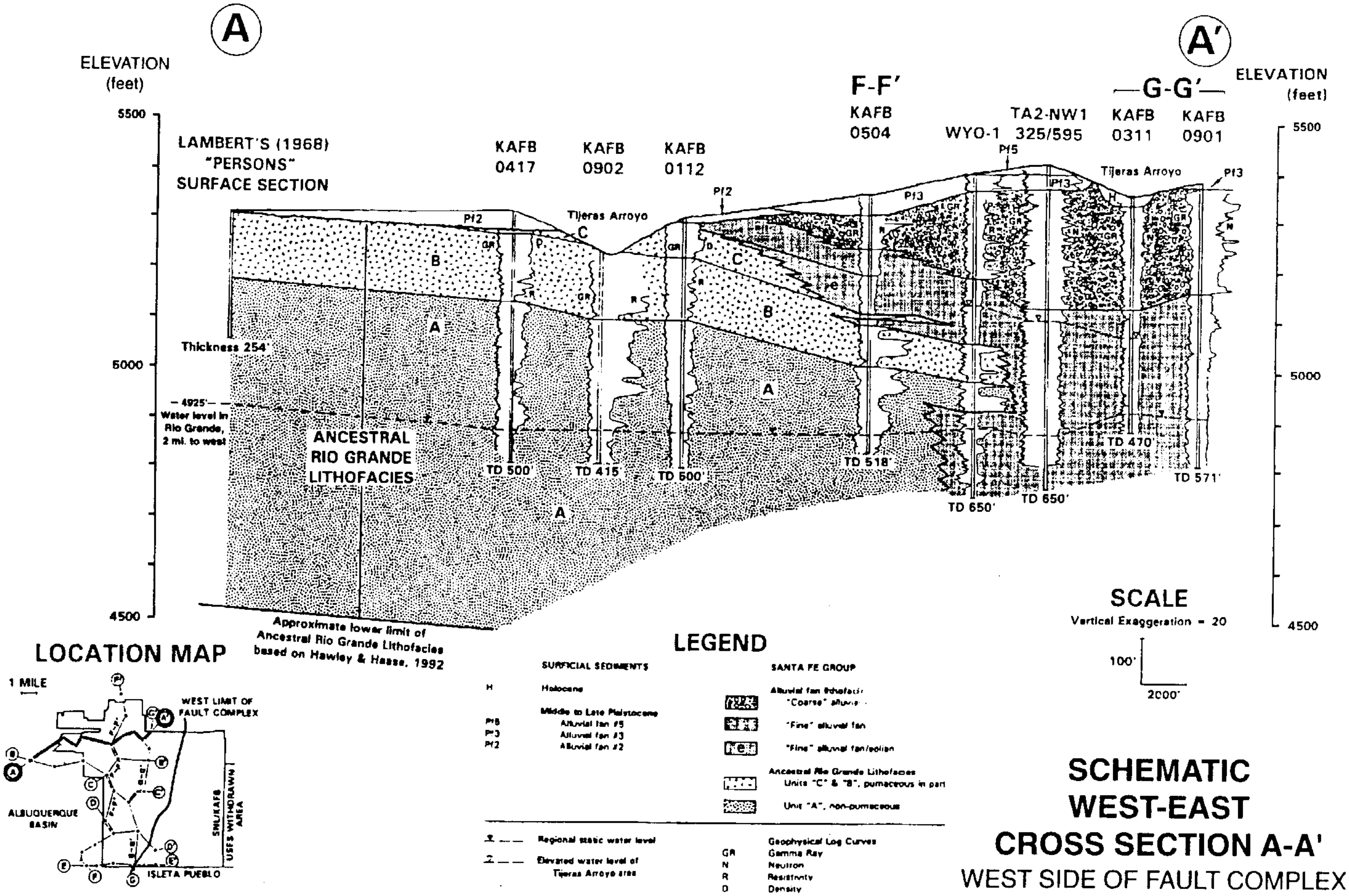
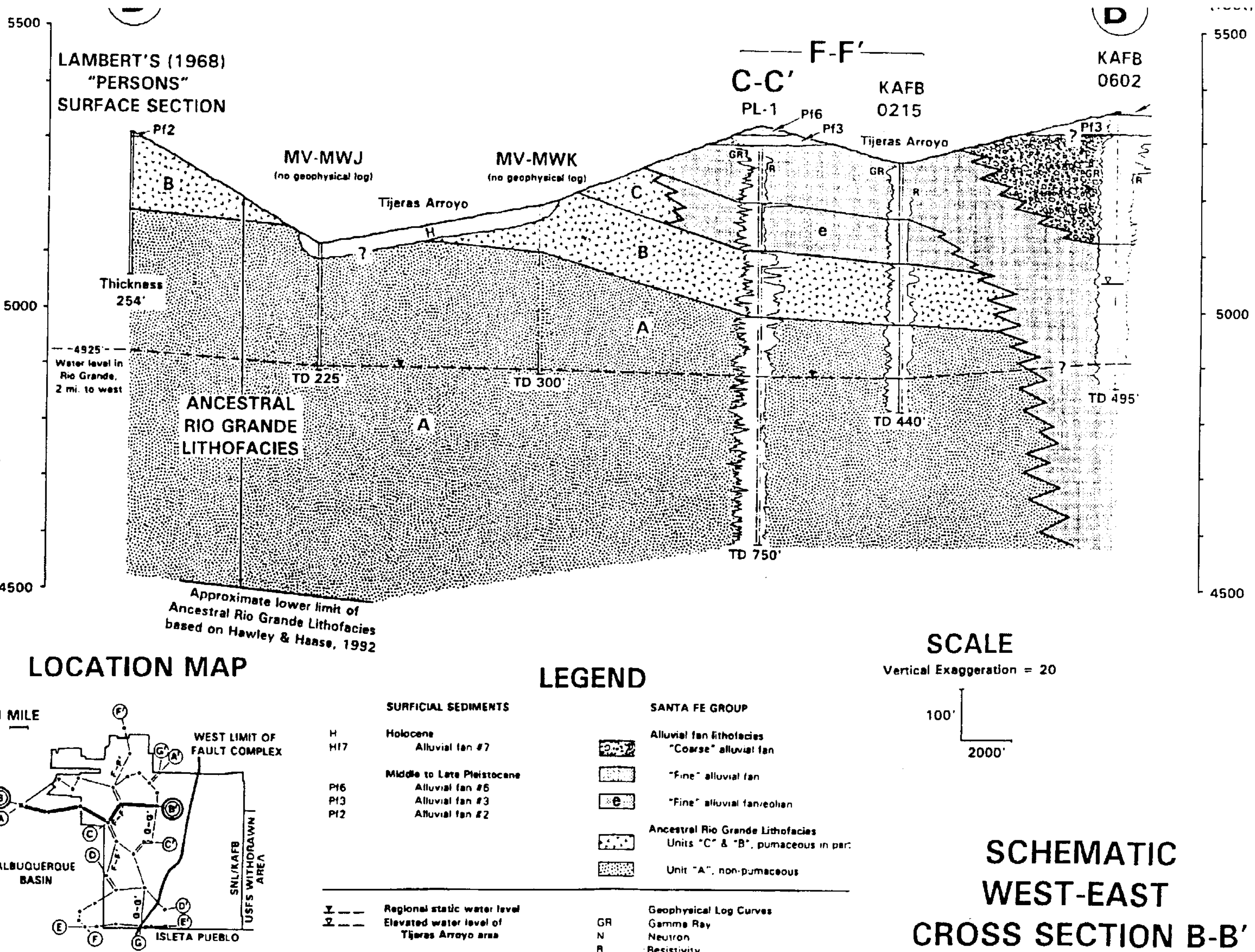


Figure 2.8. Schematic West-East Cross Section A-A' Across SNL/KAFB.


LAMBERT'S (1968)
"PERSONS"
SURFACE SECTION
Pf2
B
Thickness
254'
MV-MWJ
(no geophysical log)
TD 225'
Tijeras Arroyo
H
?
MV-MWK
(no geophysical log)
TD 300'
C-C'
F-F'
PL-1
Pf6
Pf3
GR
R
C
B
e
A
TD 750'
KAFB
0215
Tijeras Arroyo
TD 440'
KAFB
0602
Pf3
TD 495'
-4925'
Water level in Rio Grande, 2 mi. to west
ANCESTRAL
RIO GRANDE
LITHOFACIES
A
Approximate lower limit of Ancestral Rio Grande Lithofacies based on Hawley & Haase, 1992
5500
5000
4500
LOCATION MAP
1 MILE
WEST LIMIT OF FAULT COMPLEX
ALBUQUERQUE BASIN
SNL/KAFB
USFS WITHDRAWN AREA
ISLETA PUEBLO
LEGEND
SURFICIAL SEDIMENTS
H Holocene
H17 Alluvial fan #7
Middle to Late Pleistocene
Pf6 Alluvial fan #6
Pf3 Alluvial fan #3
Pf2 Alluvial fan #2
SANTA FE GROUP
Alluvial fan lithofacies
"Coarse" alluvial fan
"Fine" alluvial fan
"Fine" alluvial fan/eolian
Ancestral Rio Grande Lithofacies
Units "C" & "B", pumaceous in part
Unit "A", non-pumaceous
Regional static water level
Elevated water level of Tijeras Arroyo area
Geophysical Log Curves
GR Gamma Ray
N Neutron
R Resistivity
SCALE
Vertical Exaggeration = 20
100'
2000'
SCHEMATIC
WEST-EAST
CROSS SECTION B-B'

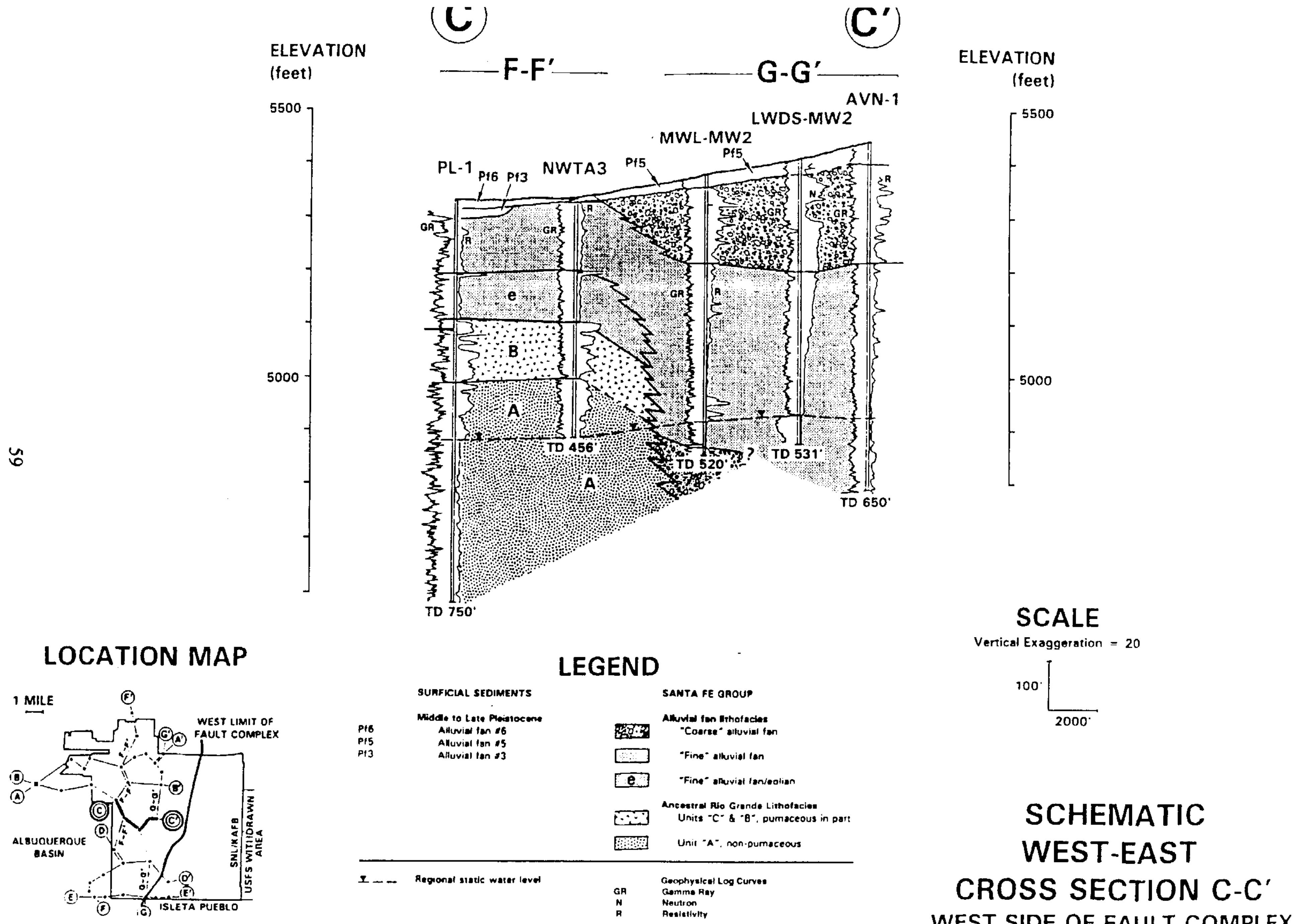
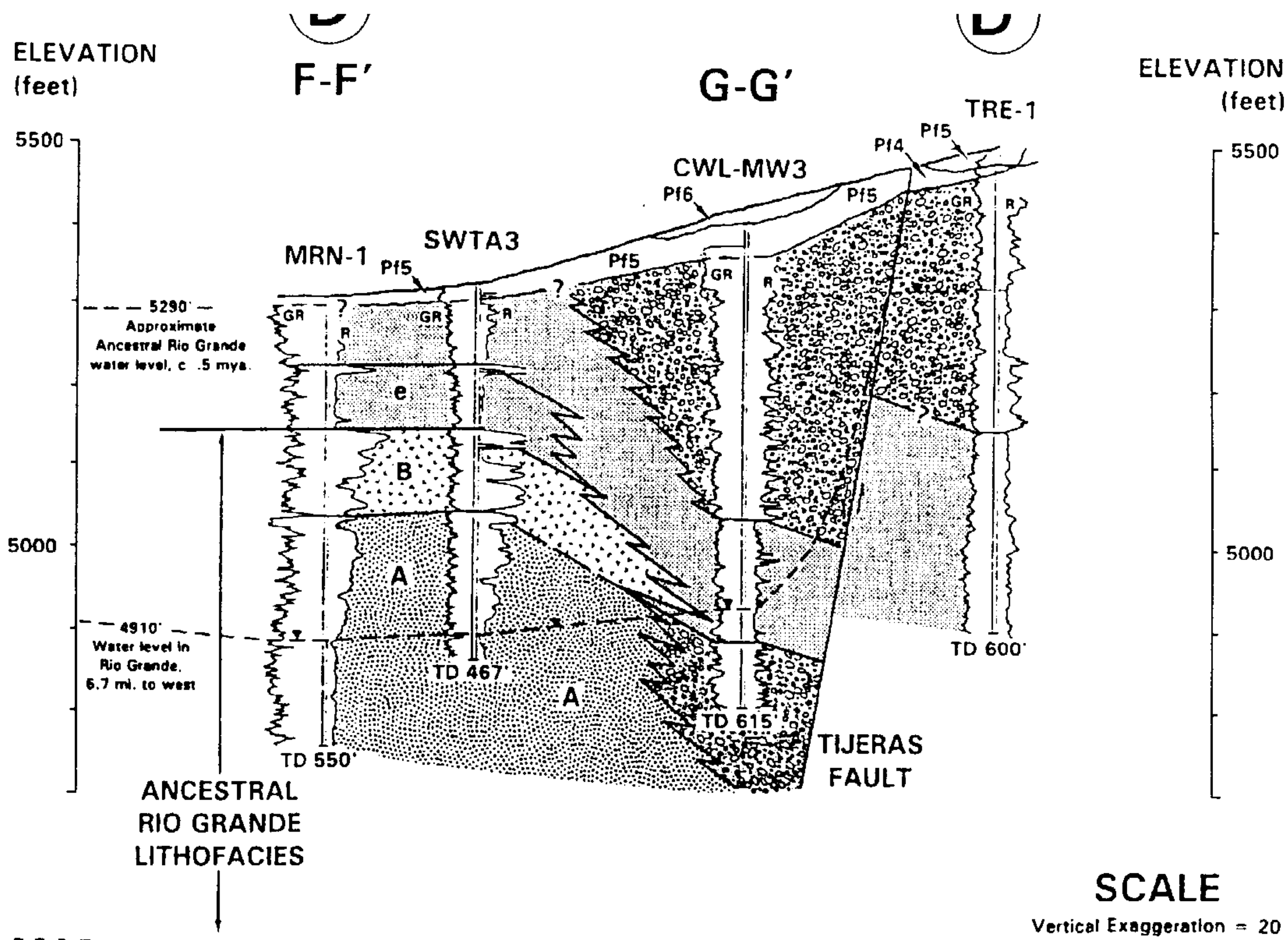
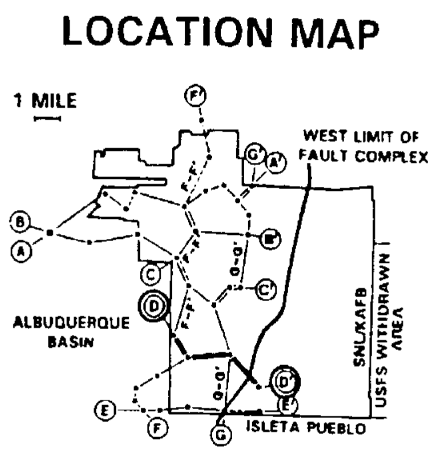
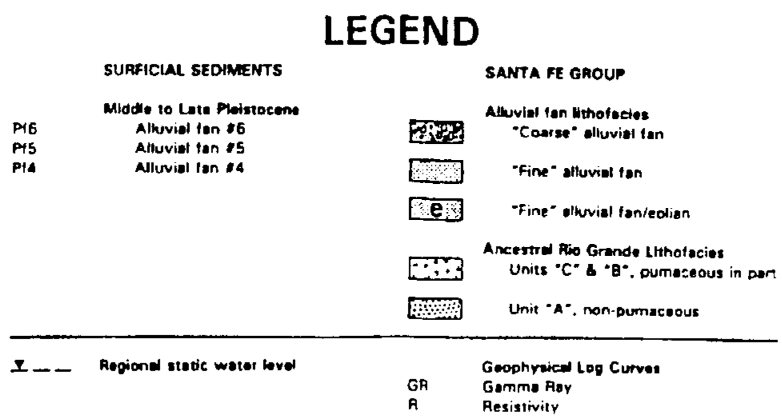


Figure 2.10 Schematic West-East Cross Section C-C' Across SNL/KAFB







SCHEMATIC
WEST-EAST
CROSS SECTION D-D'
WEST SIDE OF FAULT COMPLEX

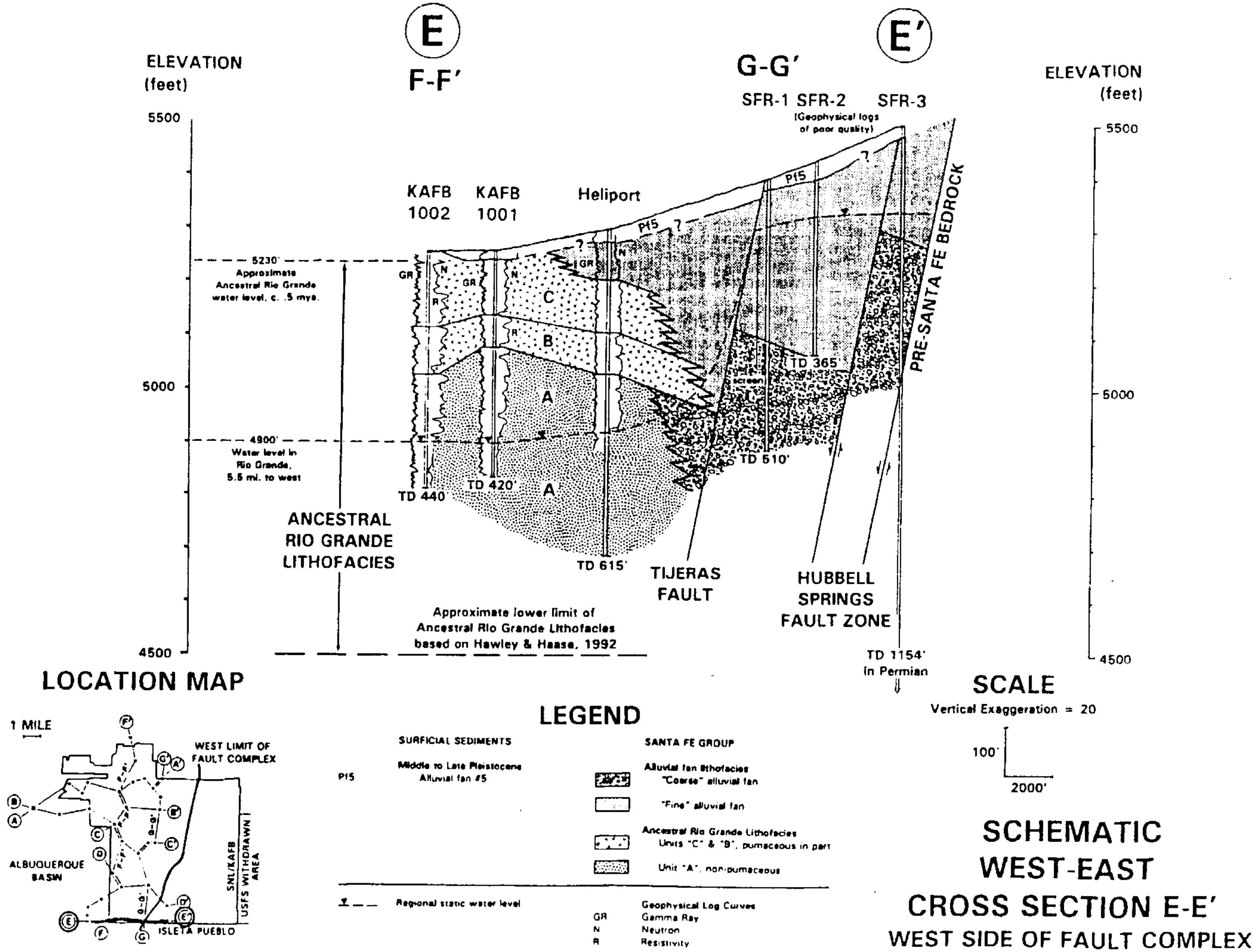


Figure 2.12. Schematic West-East Cross Section E-E' Across SNL/KAFB.

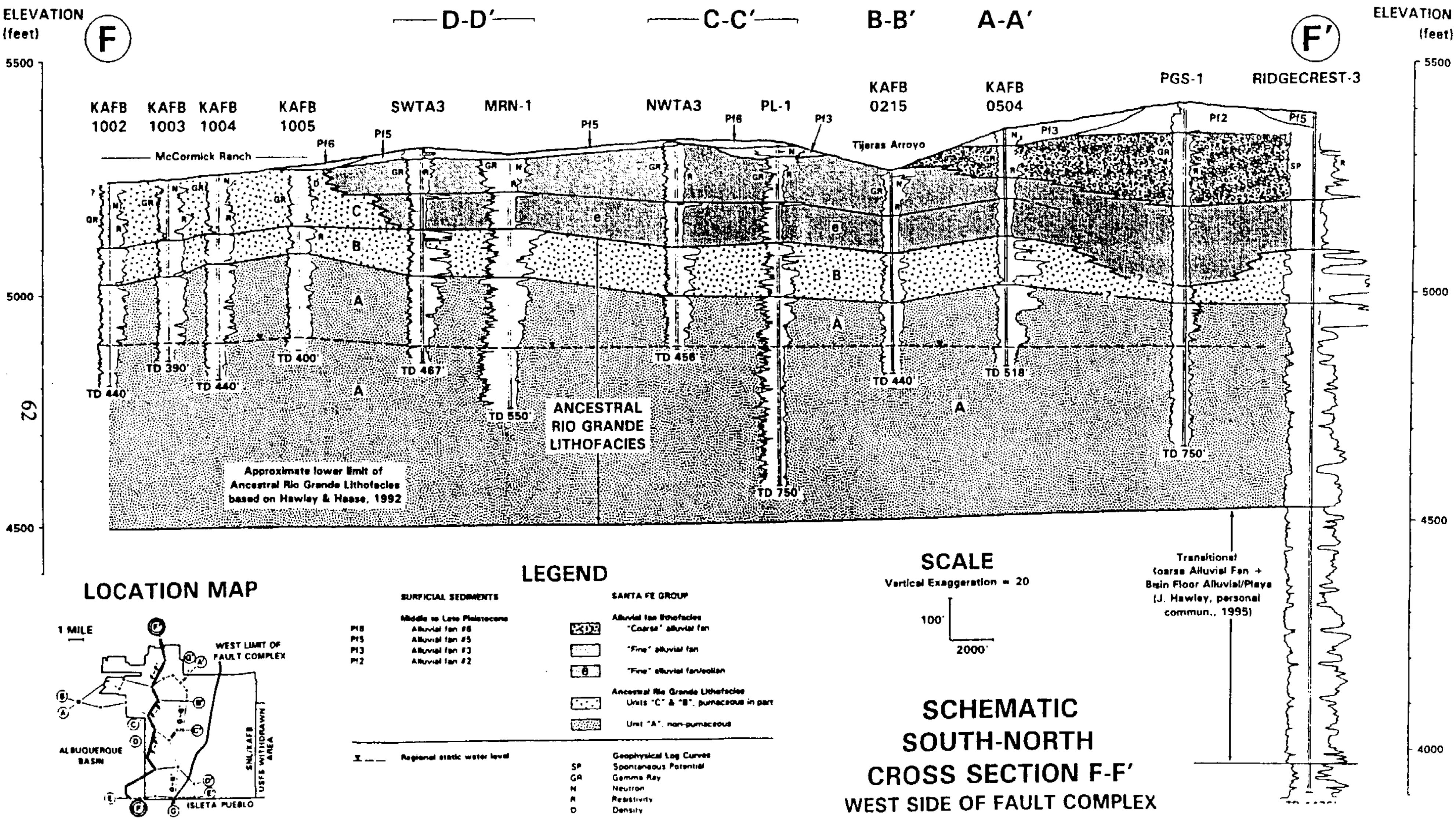


Figure 2.1.3. Schematic South-North Cross Section F-F' Across SNL/KAFB.

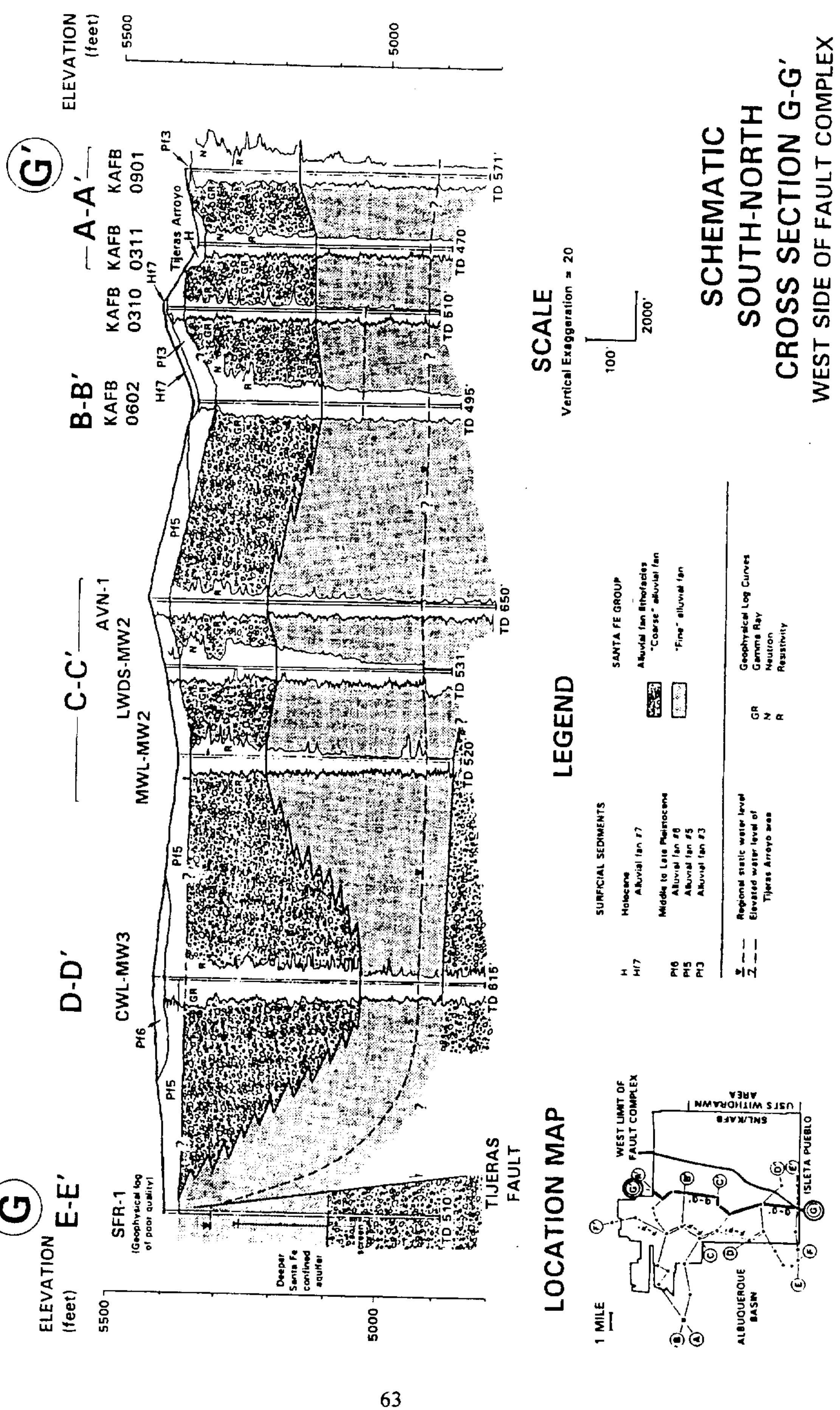


Figure 2.14. Schematic South-North Cross Section G-G′ Across SNL/KAFB.

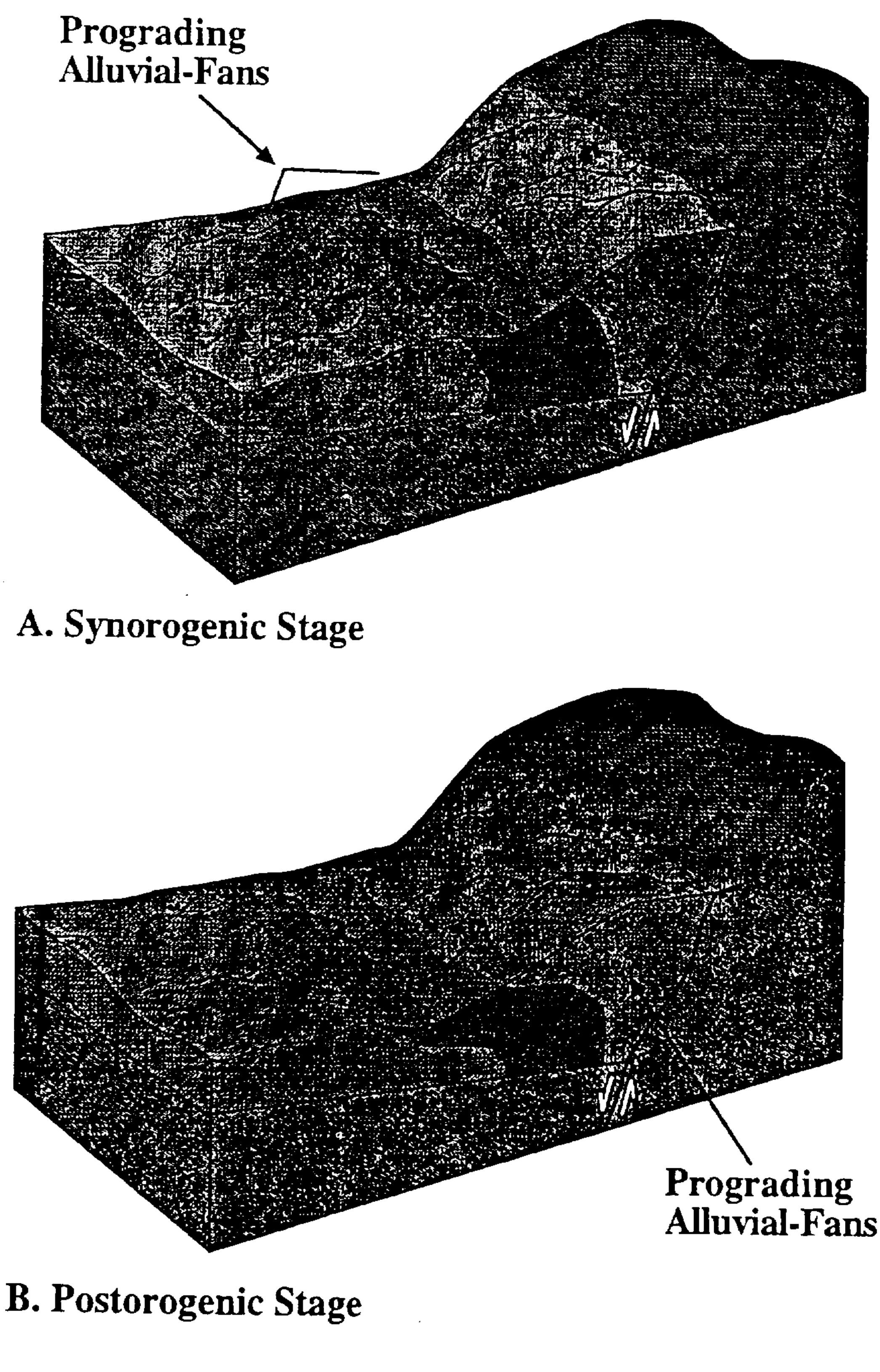


Figure 2.15. Two-Stage Depositional Model of Alluvial Fan and Axial River Sedimentation.

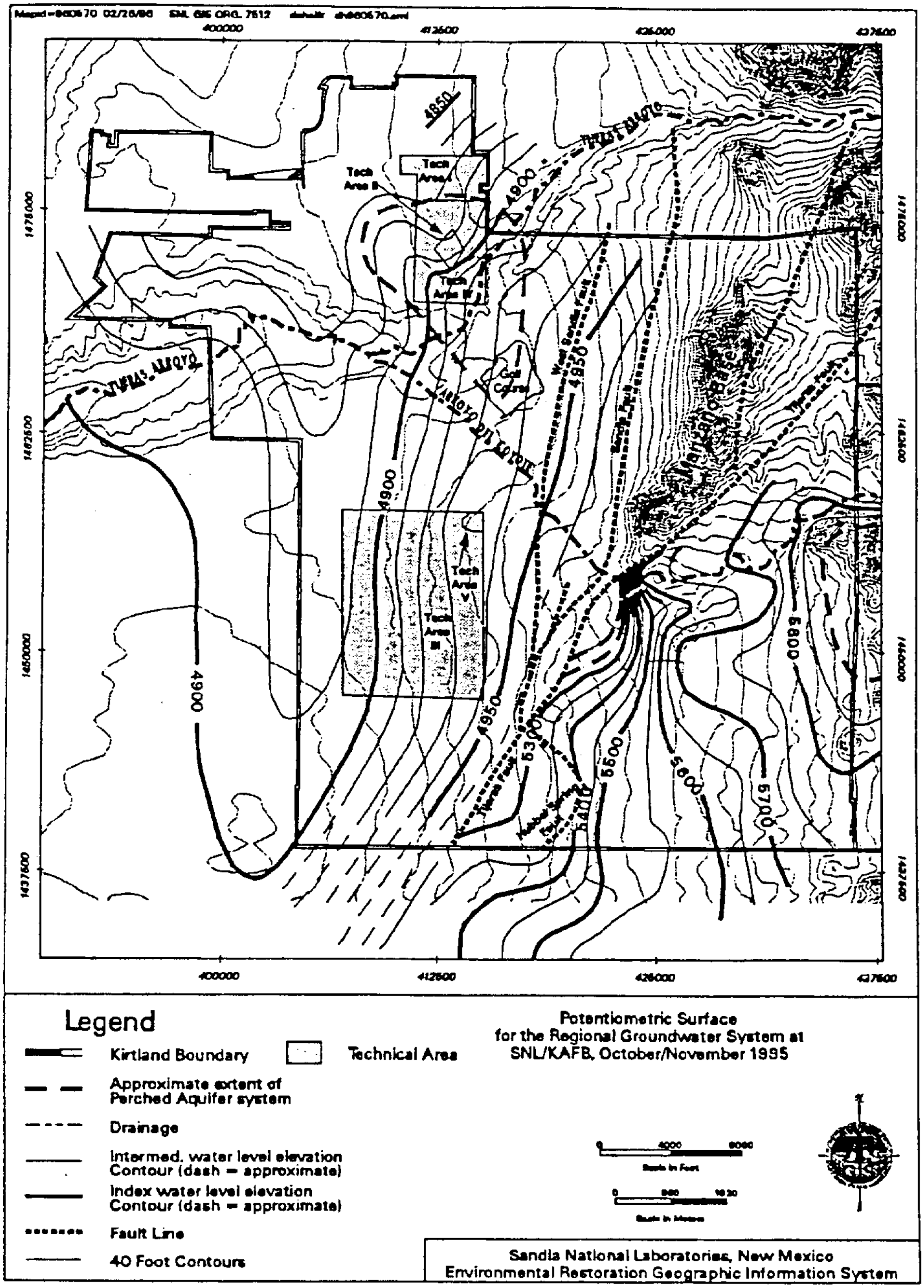


Figure 2.16. Potentiometric Surface for the Regional Groundwater System at Sandia National Laboratories/Kirtland Air Force Base, October 1995.

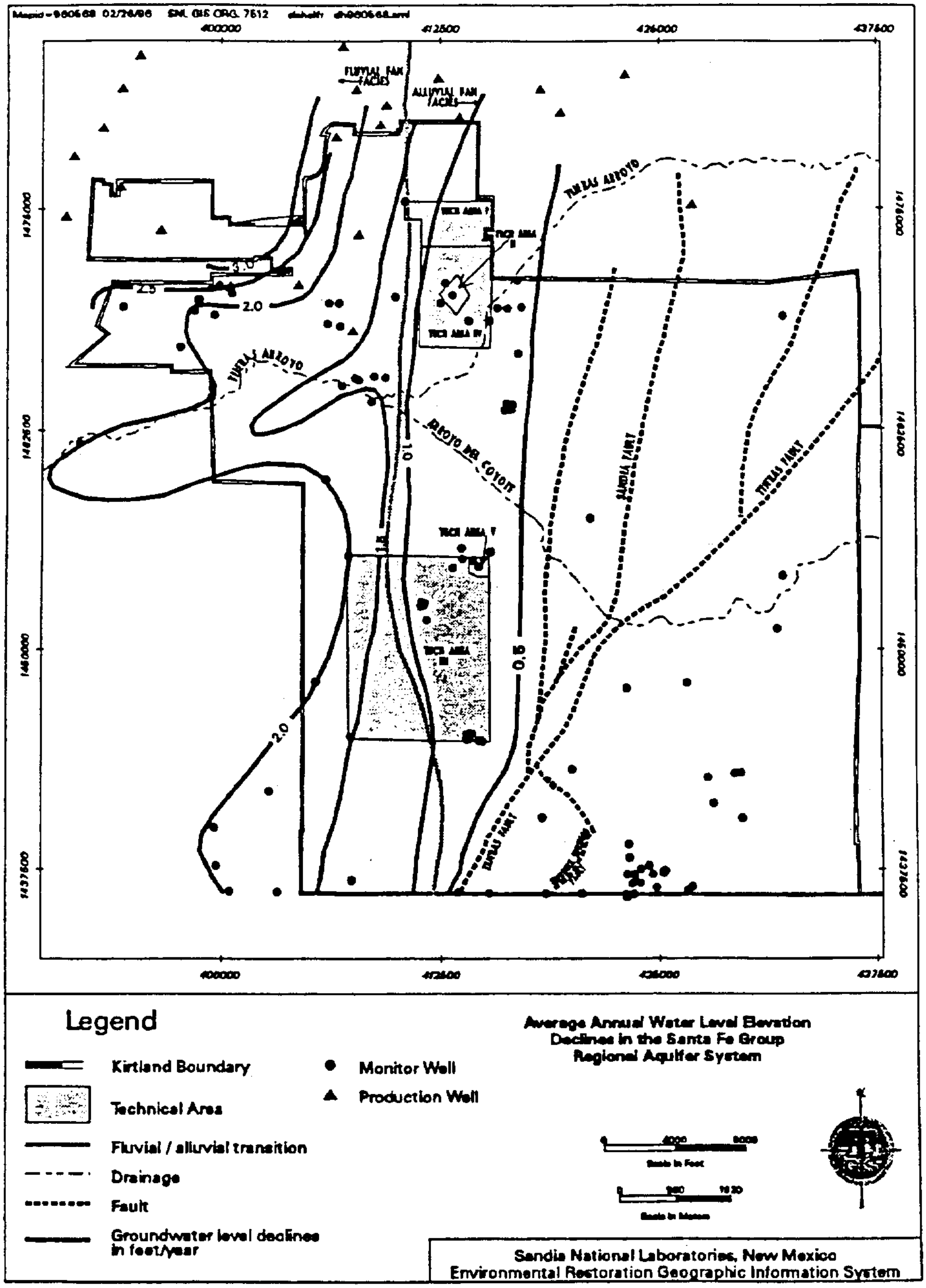
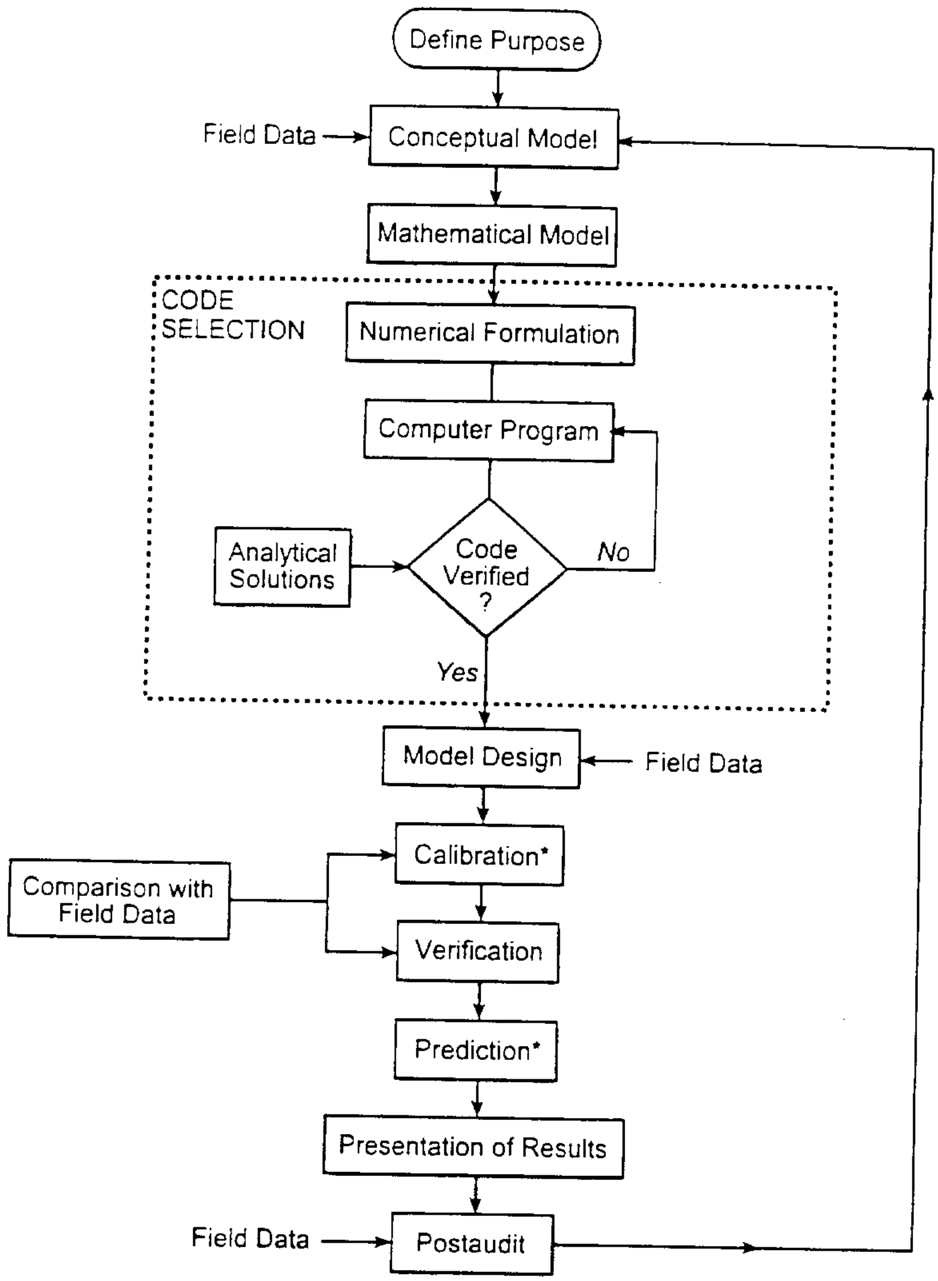


Figure 2.17. Average Annual Water Level Elevation Declines in the Santa Fe Group Regional Aquifer System.



*includes sensitivity analyses

[after Anderson and Woessner, 1992]

Figure 3.1. Steps in a Protocol for Model Application.

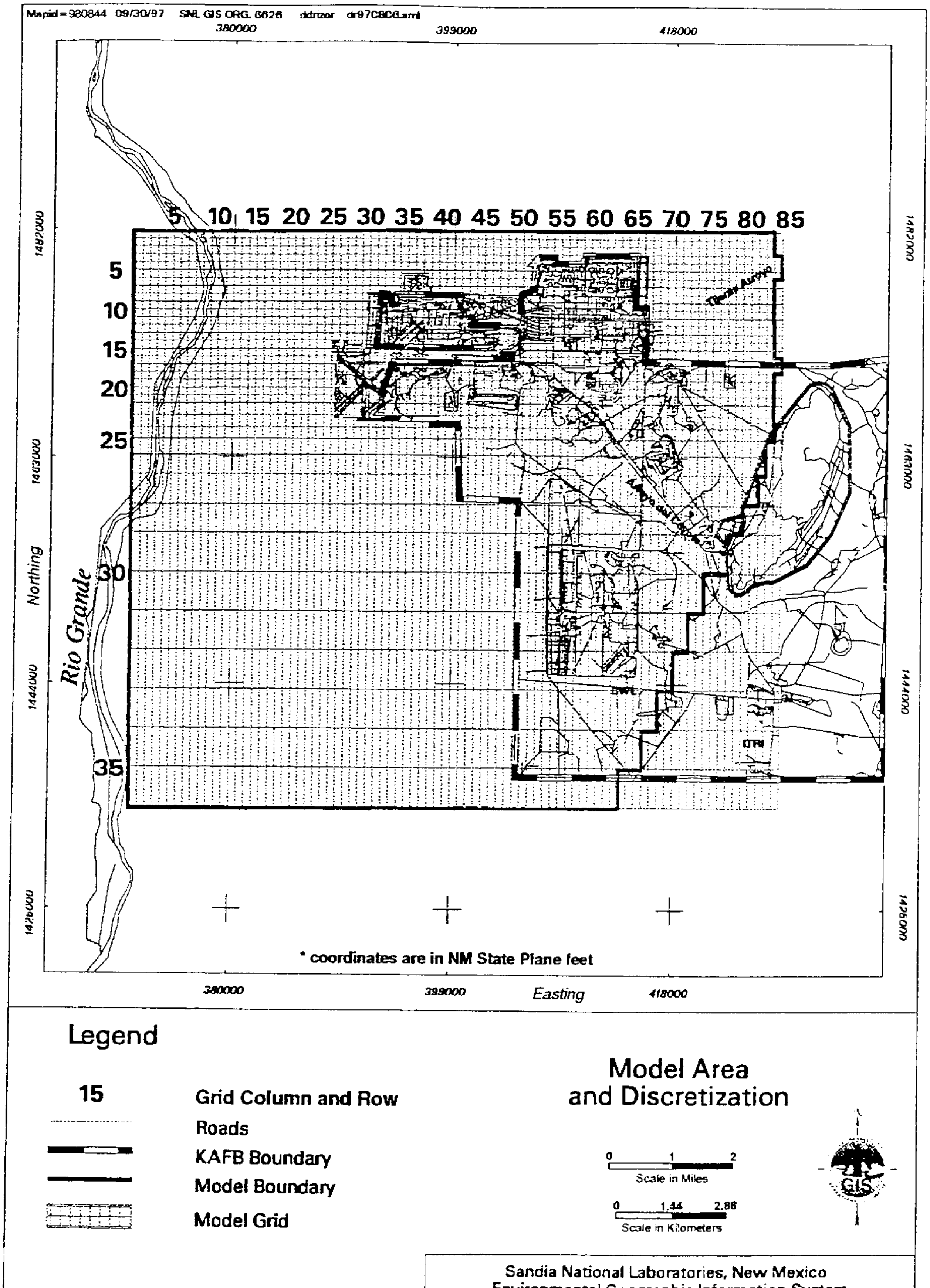


Figure 3.2. Model Area and Discretization.

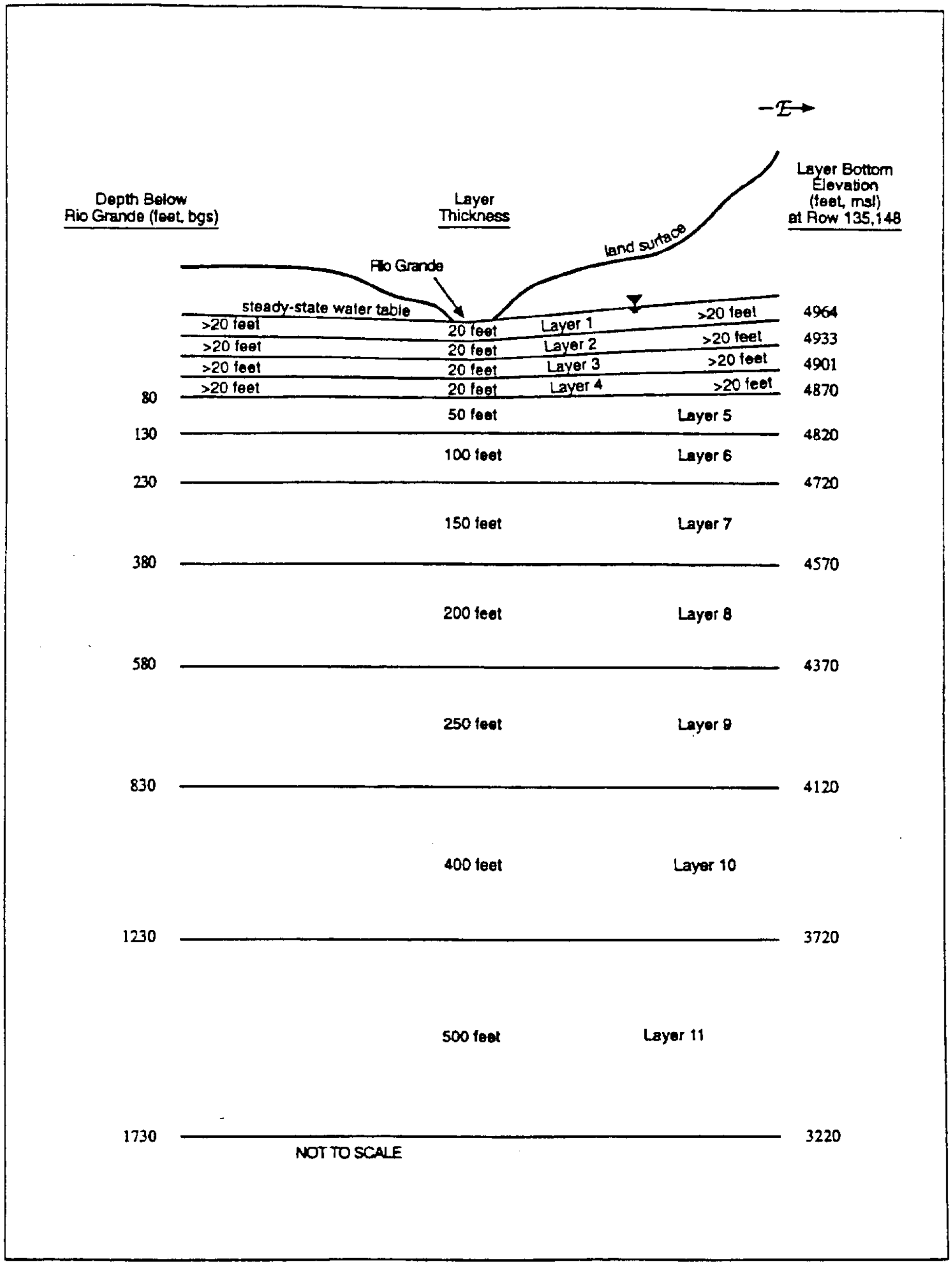


Figure 3.3. Configuration of Model Layers in the Albuquerque Basin Model.

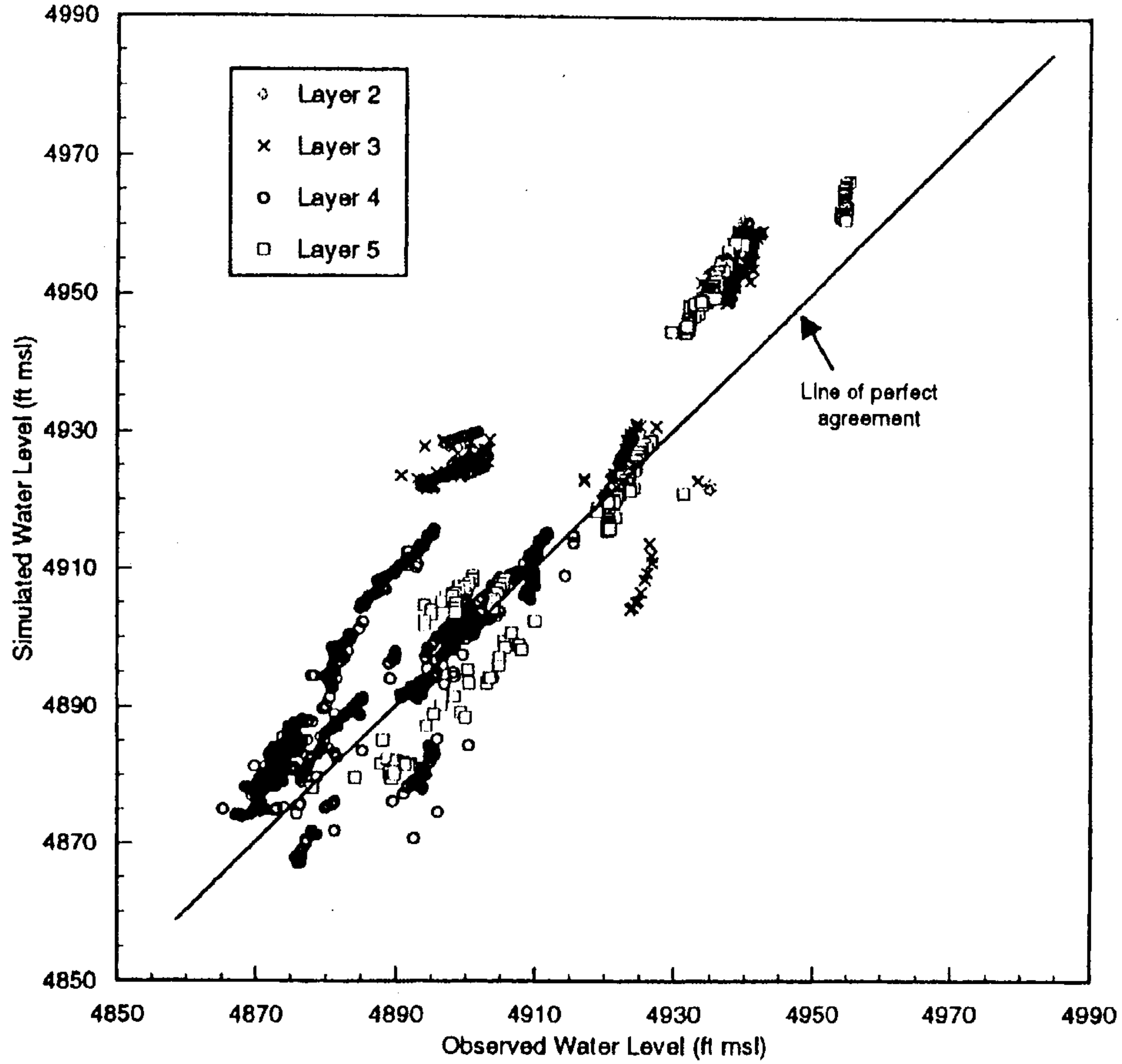
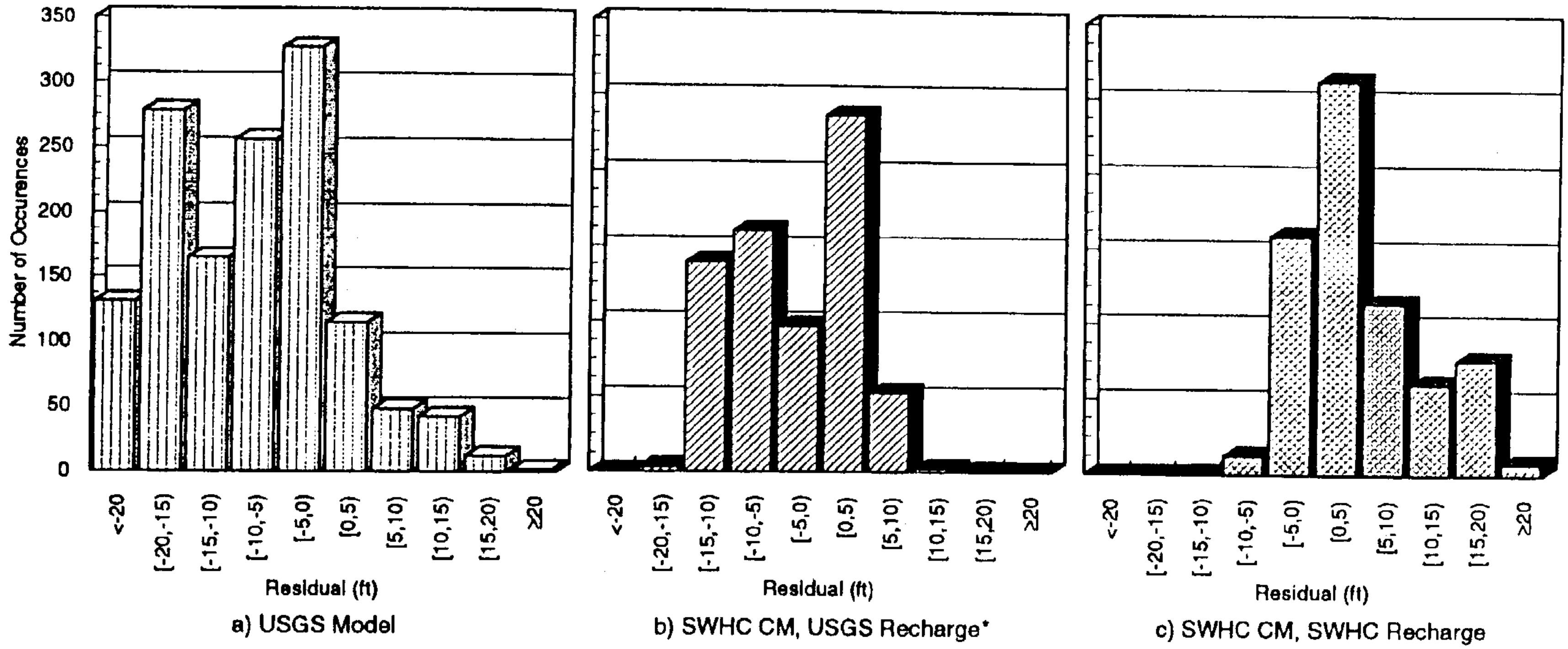
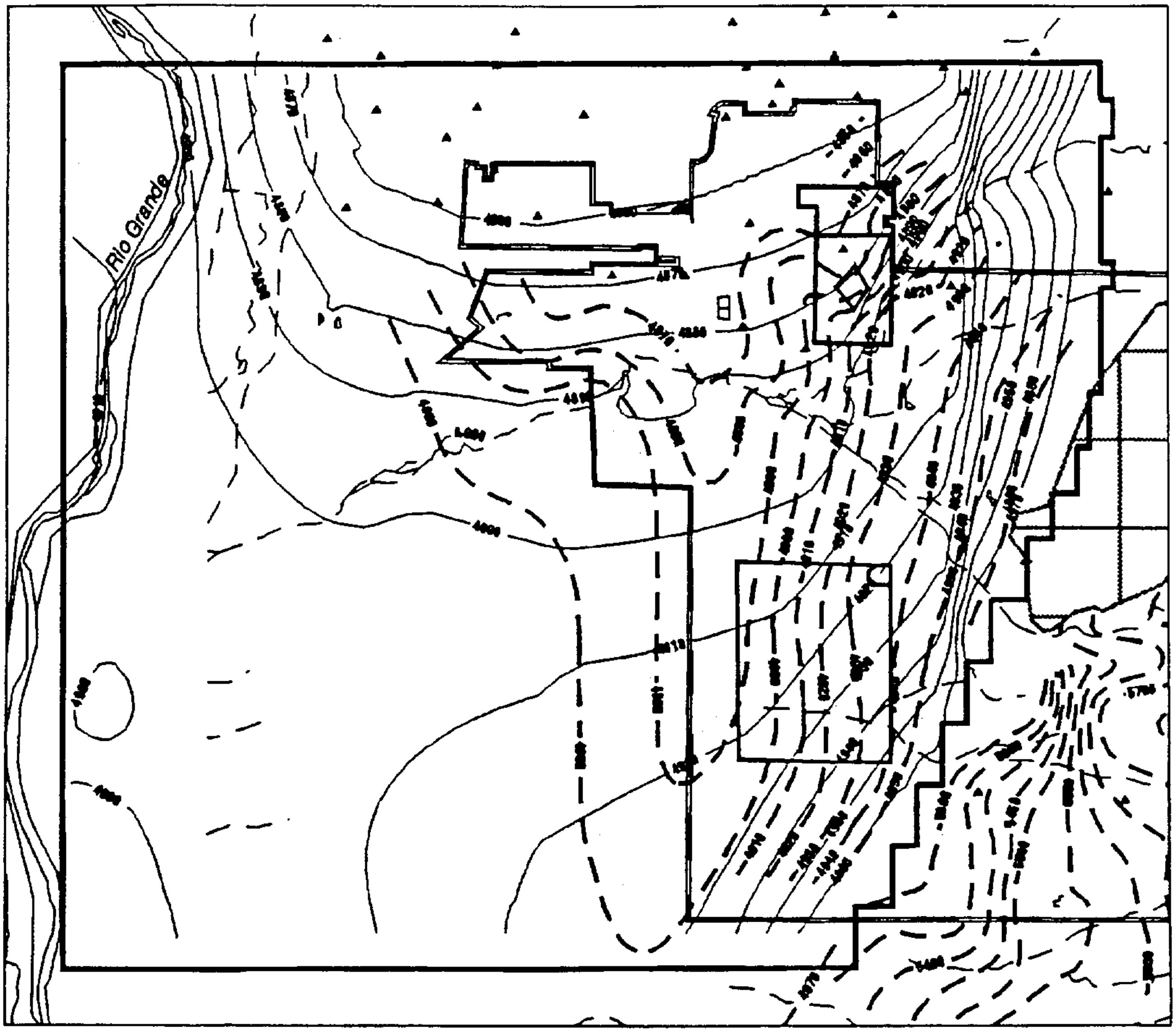


Figure 4.1. Observed versus Calibrated Water Levels, USGS Model.



*Tijeras Arroyo recharge only

Figure 4.2. Histogram of Residuals, USGS Model; SWHC CM, USGS Recharge; SWHC CM, SWHC Recharge.



Modeled Groundwater Surface, Layer 4

Conceptual Model: USGS
Recharge: USGS

Legend

- ▲ Production Well
- 10 ft. Modeled Contour Interval
- 10 ft. Observed Contour Interval
- Surface Water
- Tech Areas
- Manzano Base
- KAFB Boundary
- Model Boundary

Figure 4.3. Simulated Water Levels, March 1995, Layer 4, USGS Model.

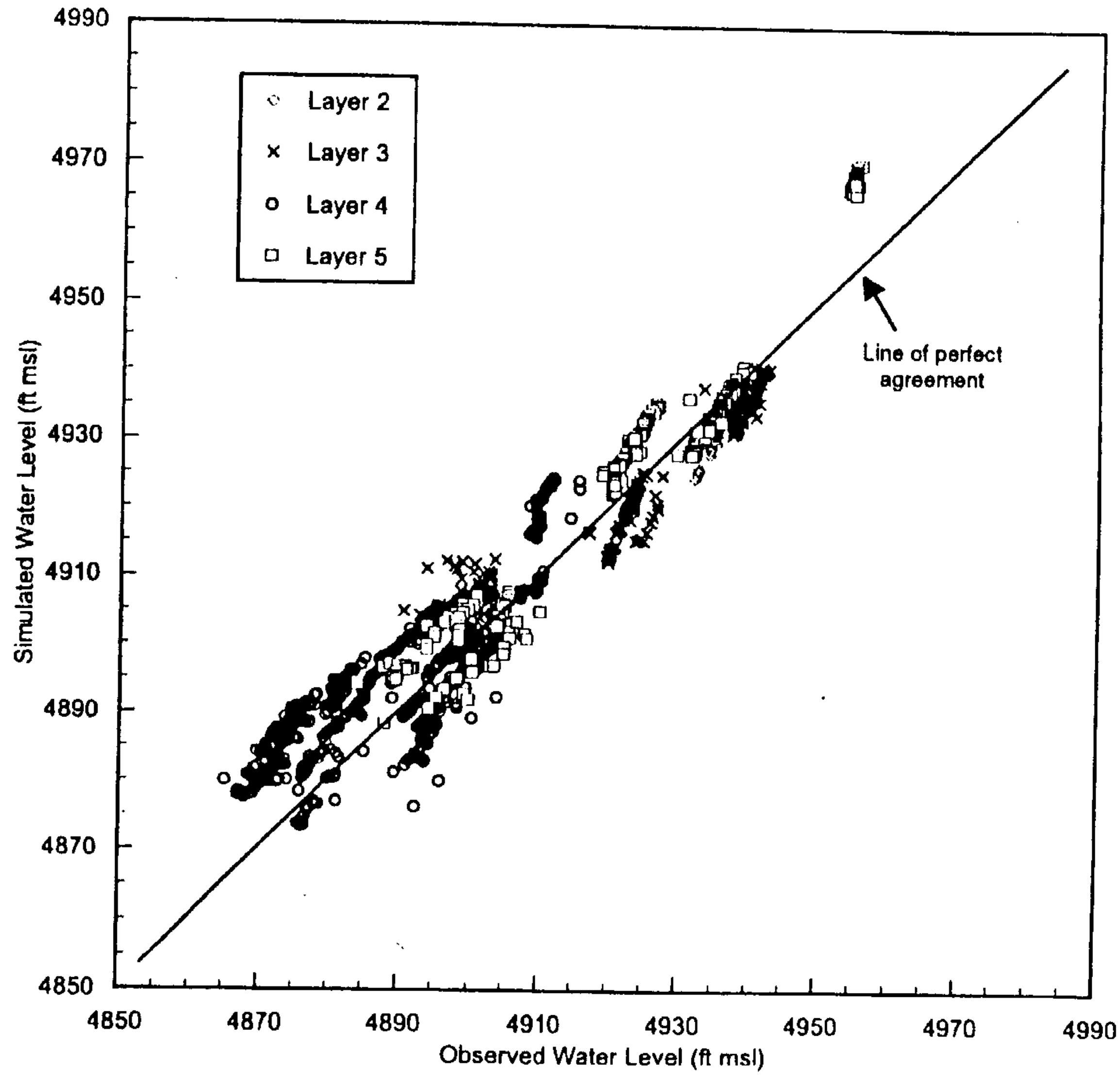


Figure 4.4. Observed versus Calibrated Water Levels, SWHC CM, USGS Recharge.

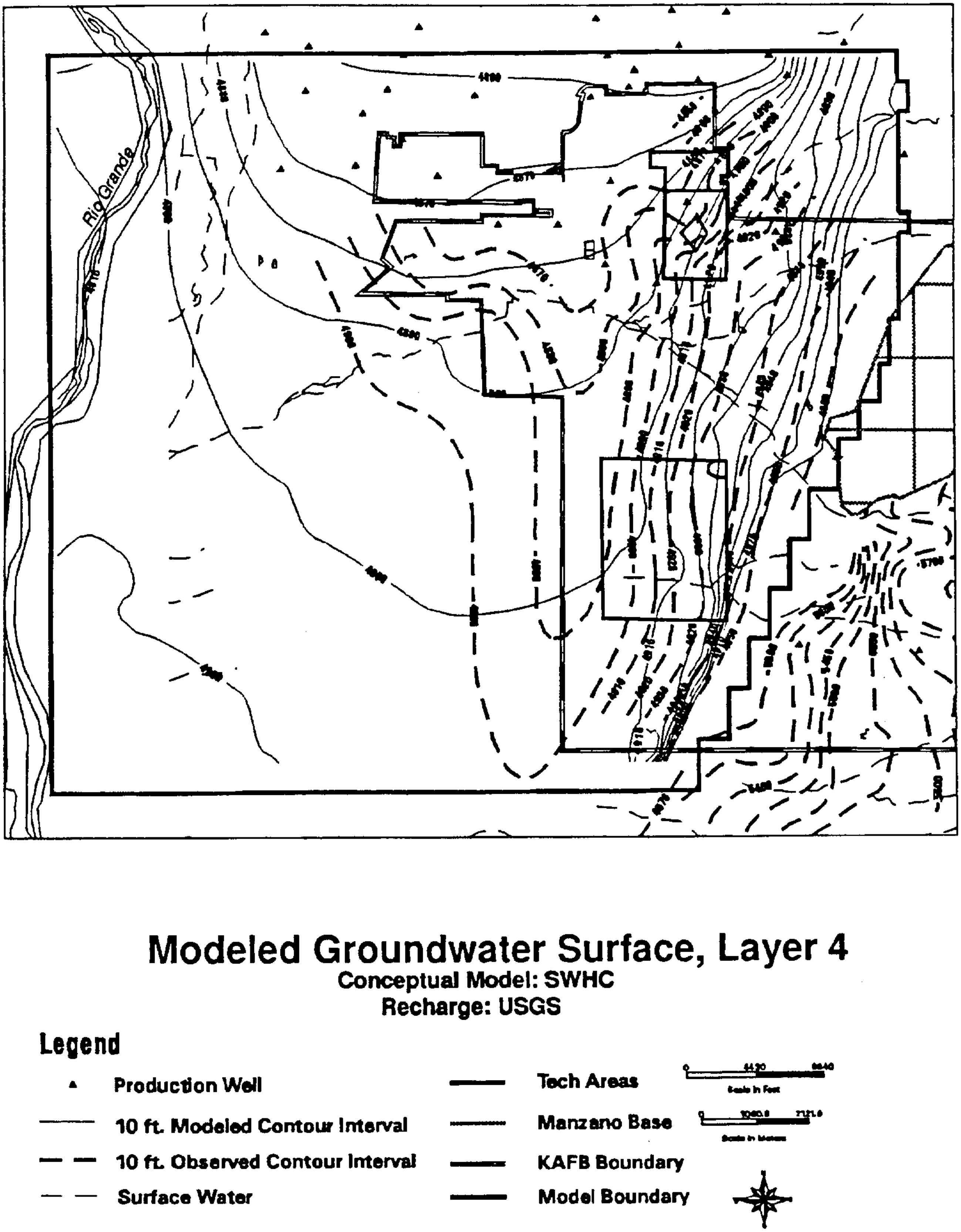


Figure 4.5 Simulated Water Levels, March 1995, Layer 4, SWHC CM, USGS Recharge

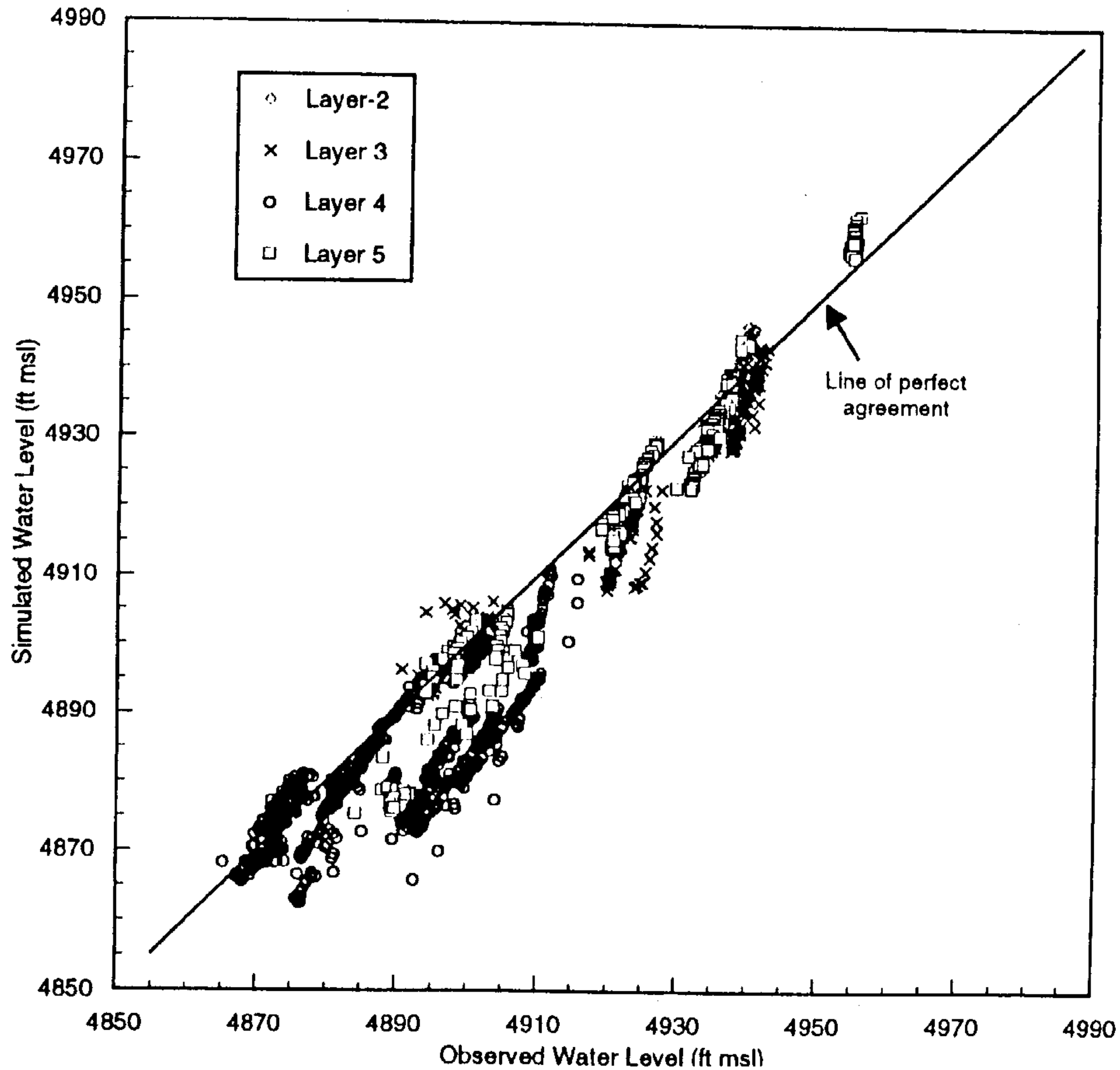
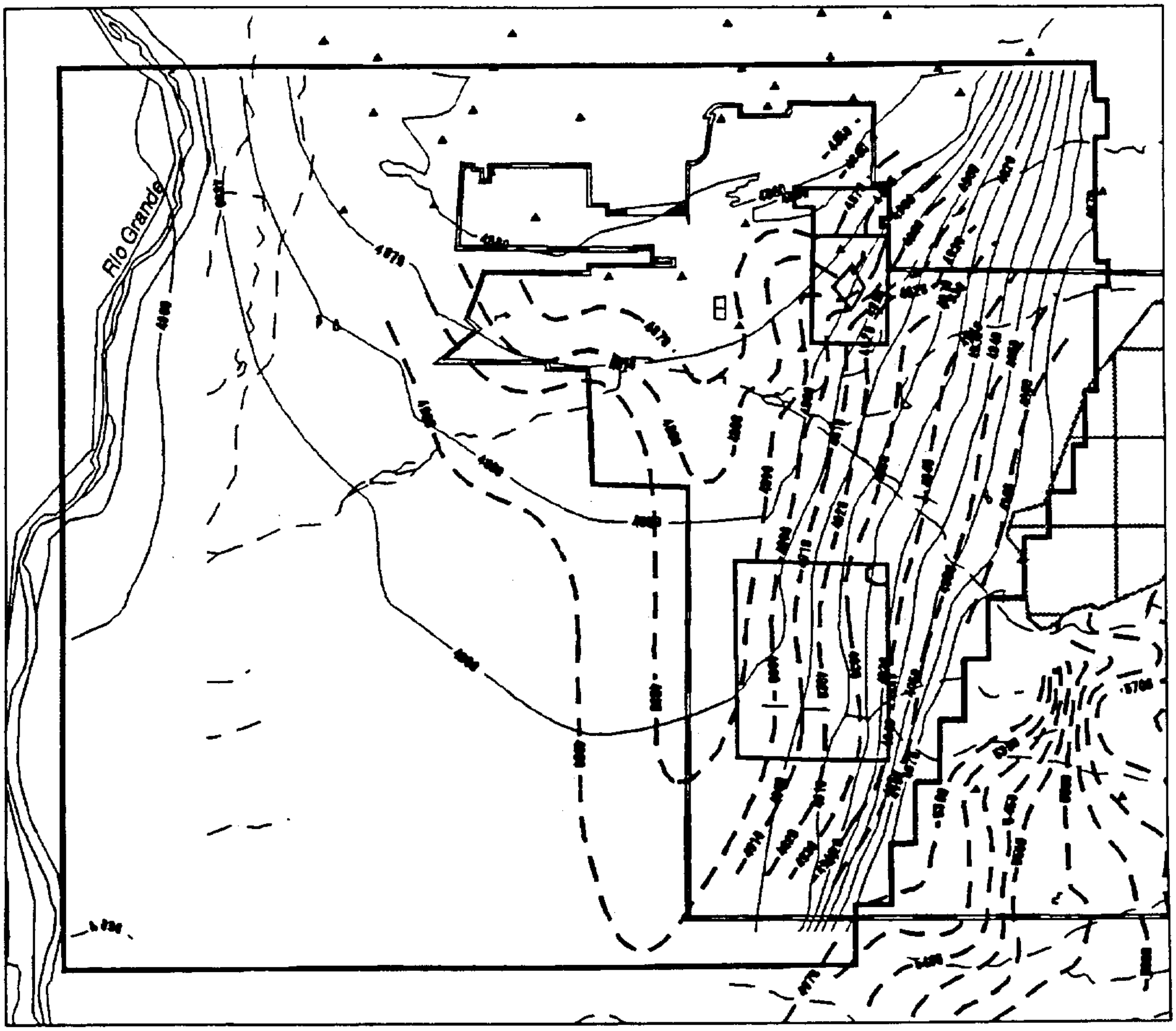


Figure 4.6. Observed versus Calibrated Water Levels, SWHC CM, SWHC Recharge.



Modeled Groundwater Surface, Layer 4

Conceptual Model: SWHC
Recharge: SWHC

Legend

- Production Well
- 10 ft. Modeled Contour Interval
- 10 ft. Observed Contour Interval
- Surface Water
- Tech Areas
- Manzano Base
- KAFB Boundary
- Model Boundary

Figure 4.7 Simulated Water Levels and Residuals, March 1995, Layer 4, SWHC CM, SWHC Recharge.

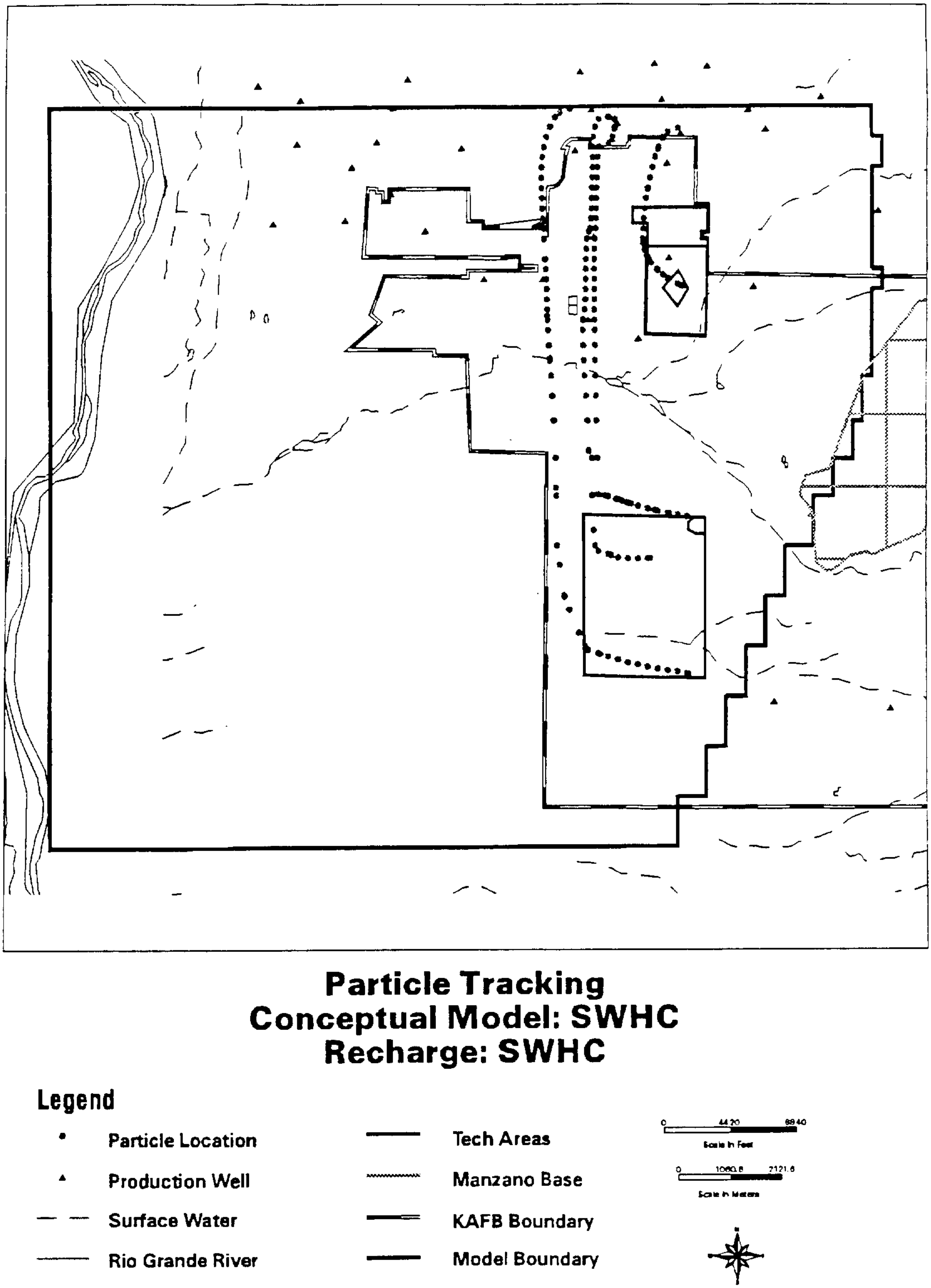


Figure 4.8 Forward Particle Tracking Results for Calibrated Flow Field.

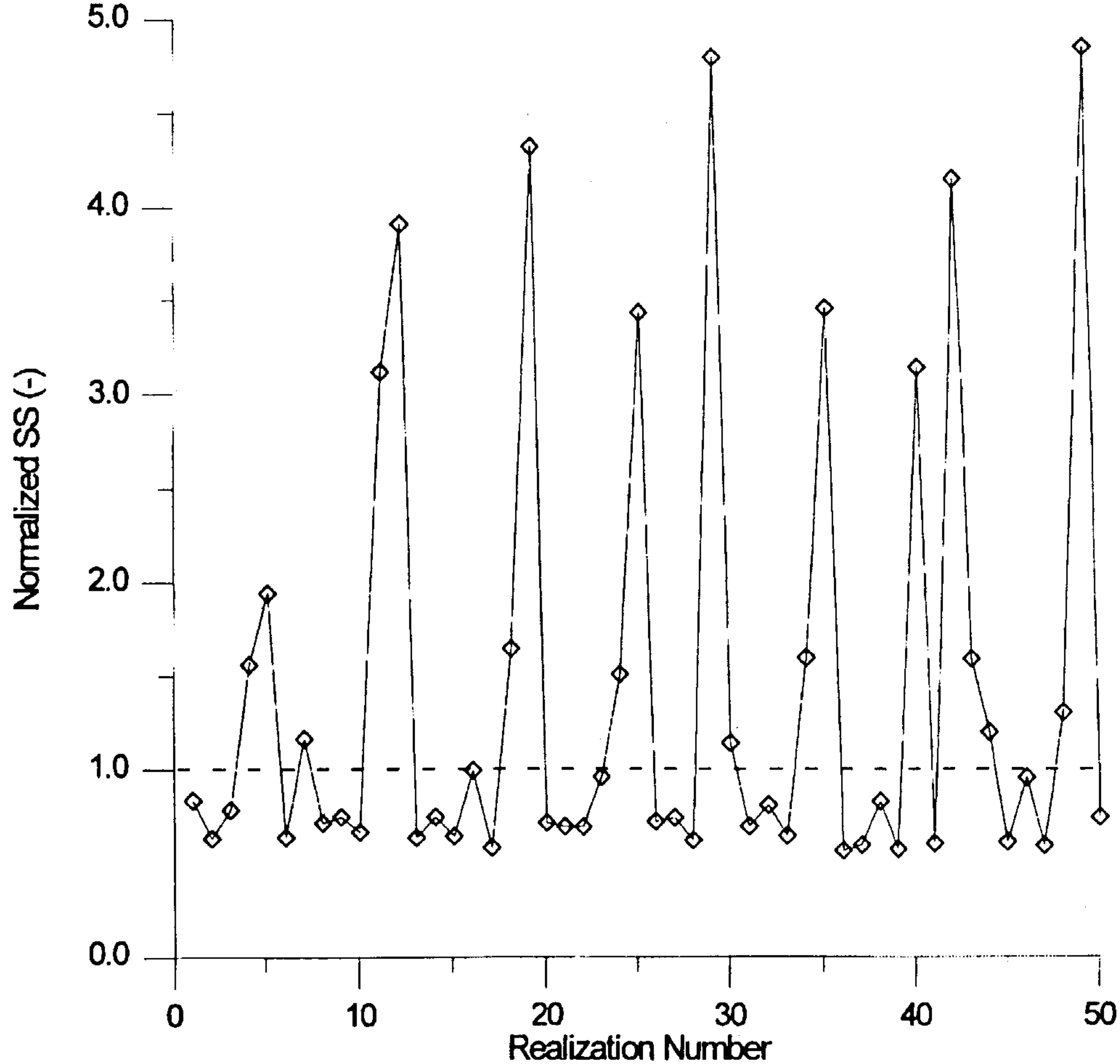


Figure 4.9 Normalized Residual Sum of Squares for 50 Monte Carlo Realizations

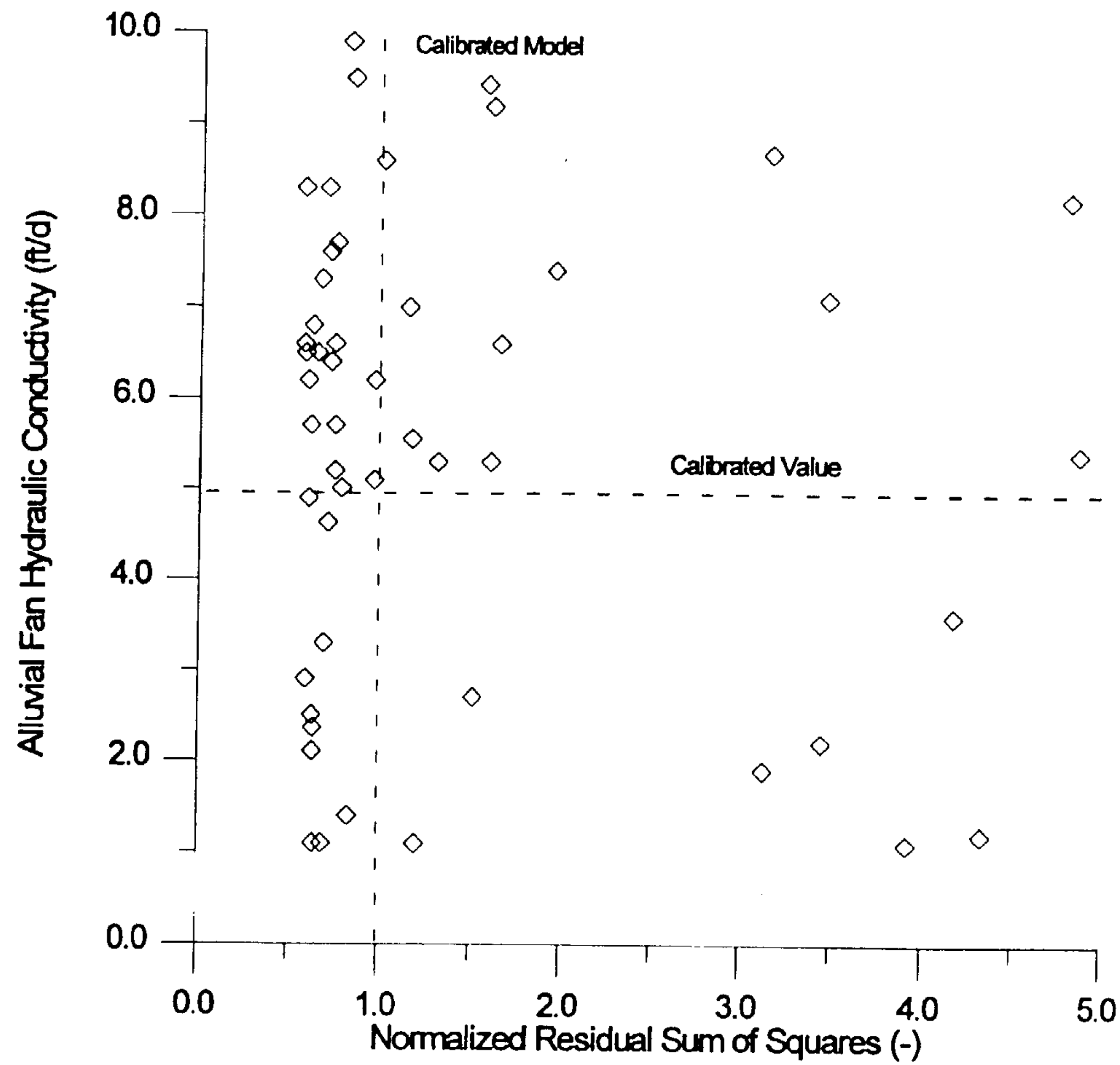


Figure 4.10 Normalized Residual Sum of Squares versus Alluvial Fan Hydraulic Conductivity

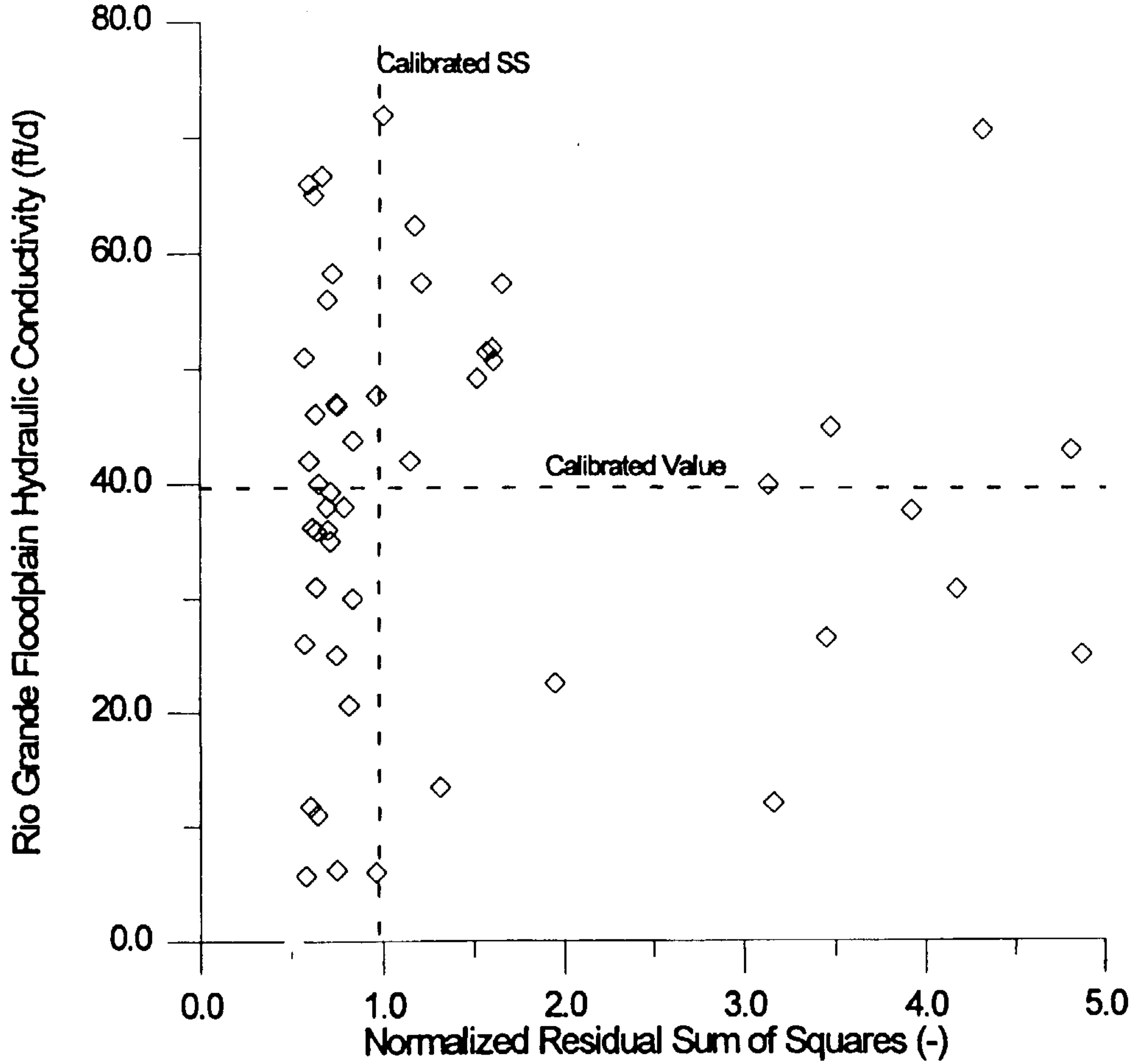


Figure 4.11 Normalized Residual Sum of Squares versus Rio Grande Floodplain Hydraulic Conductivity

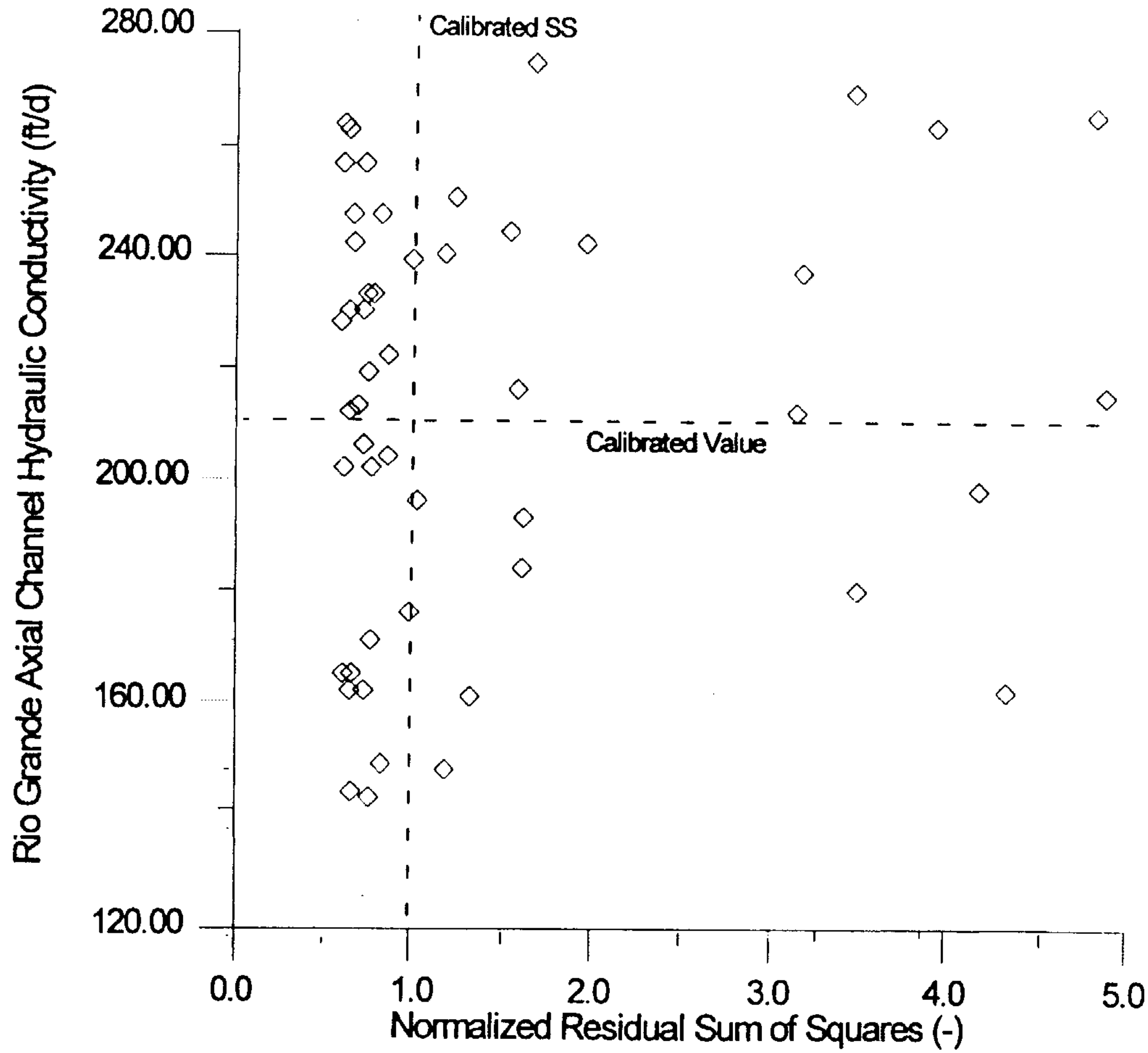


Figure 4.12 Normalized Residual Sum of Squares versus Rio Grande Axial Channel Hydraulic Conductivity

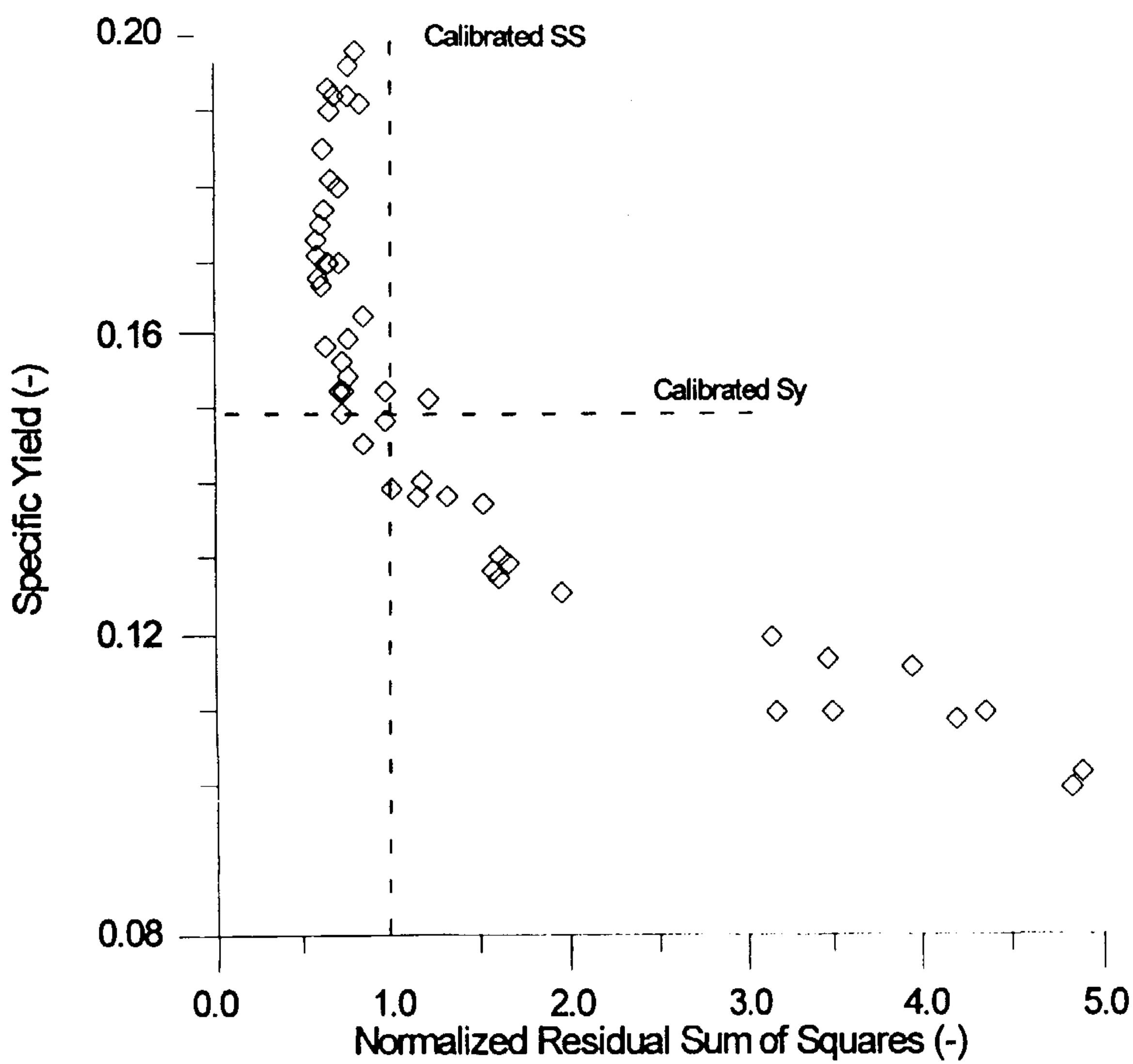


Figure 4.13 Normalized Residual Sum of Squares versus Specific Yield

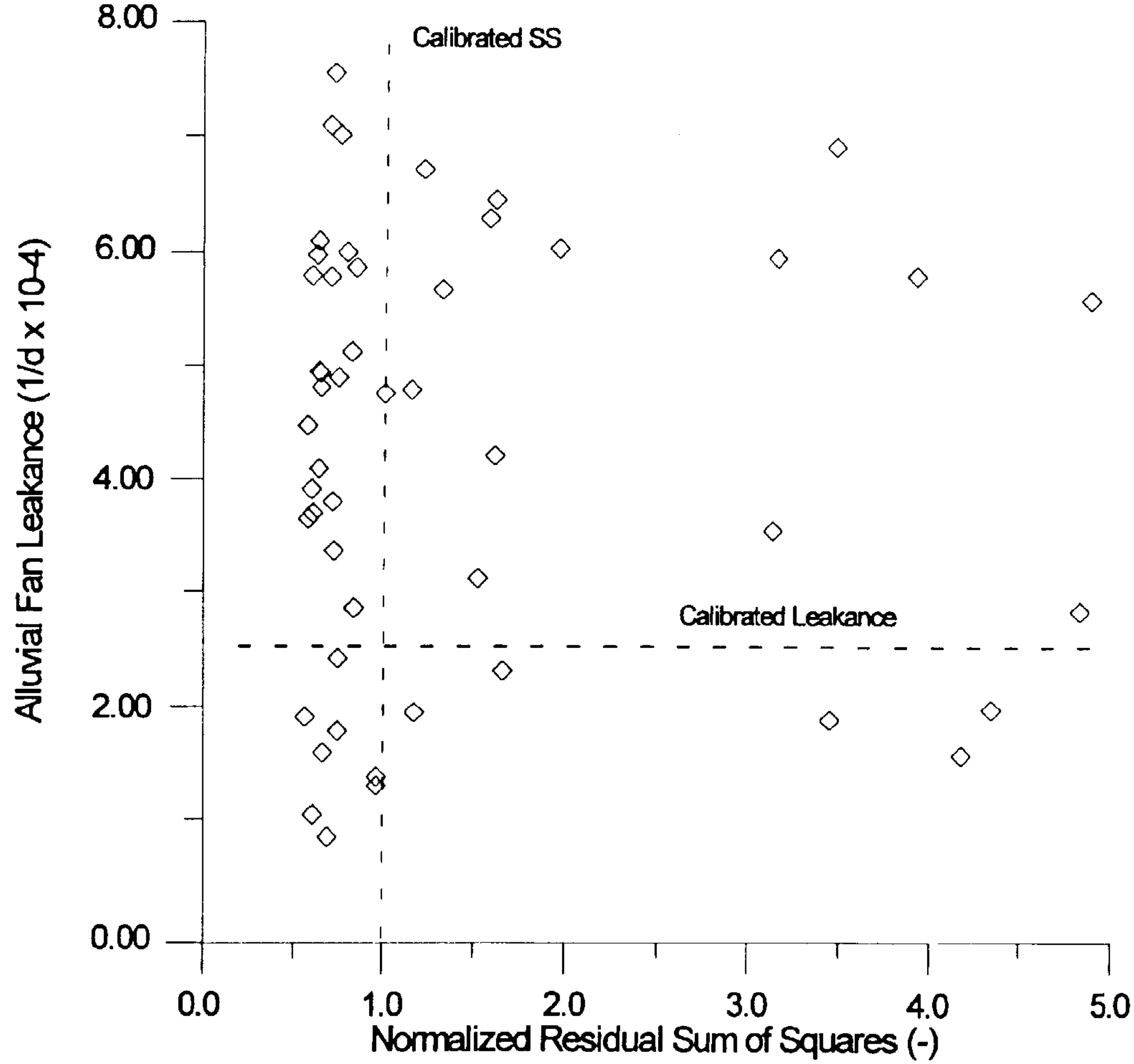


Figure 4.14 Normalized Residual Sum of Squares versus Alluvial Fan Leakance

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APPENDIX A

Hydrographs from Calibrated Model

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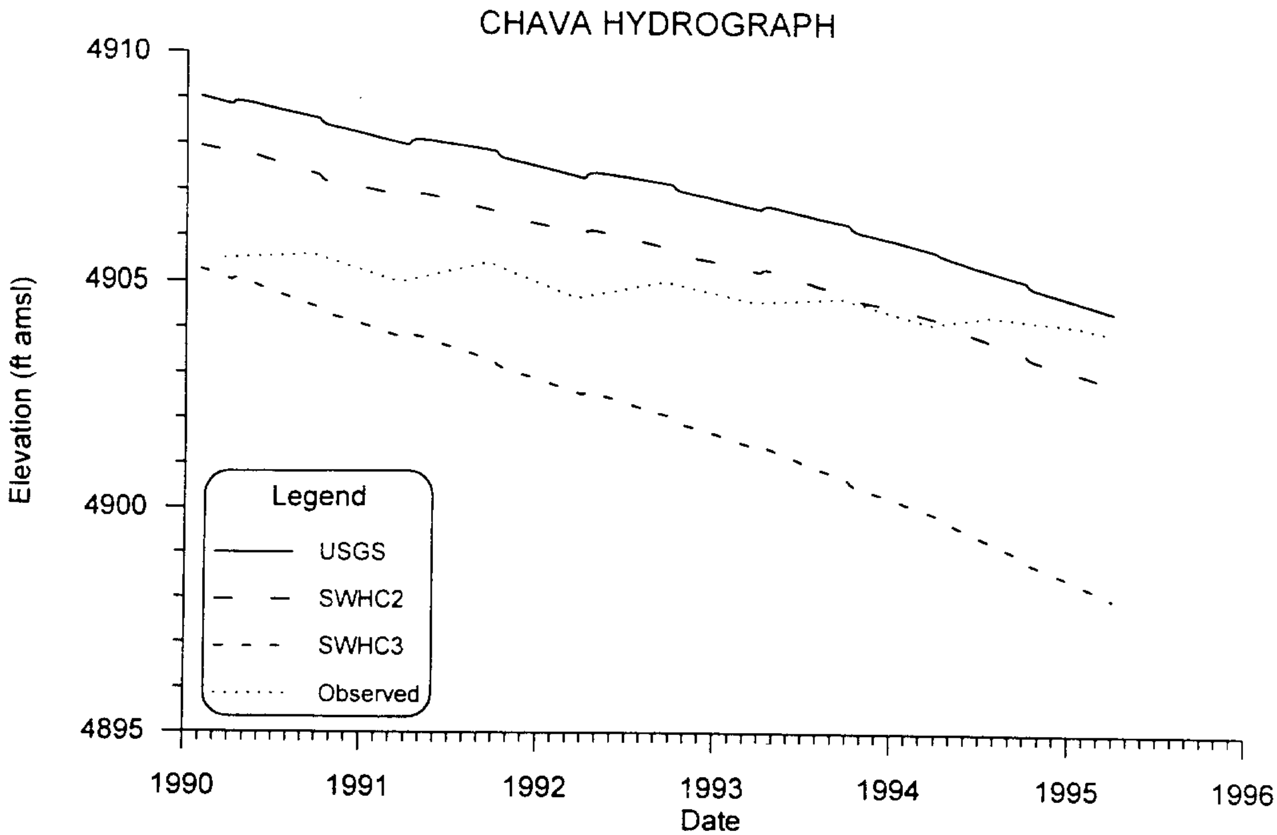
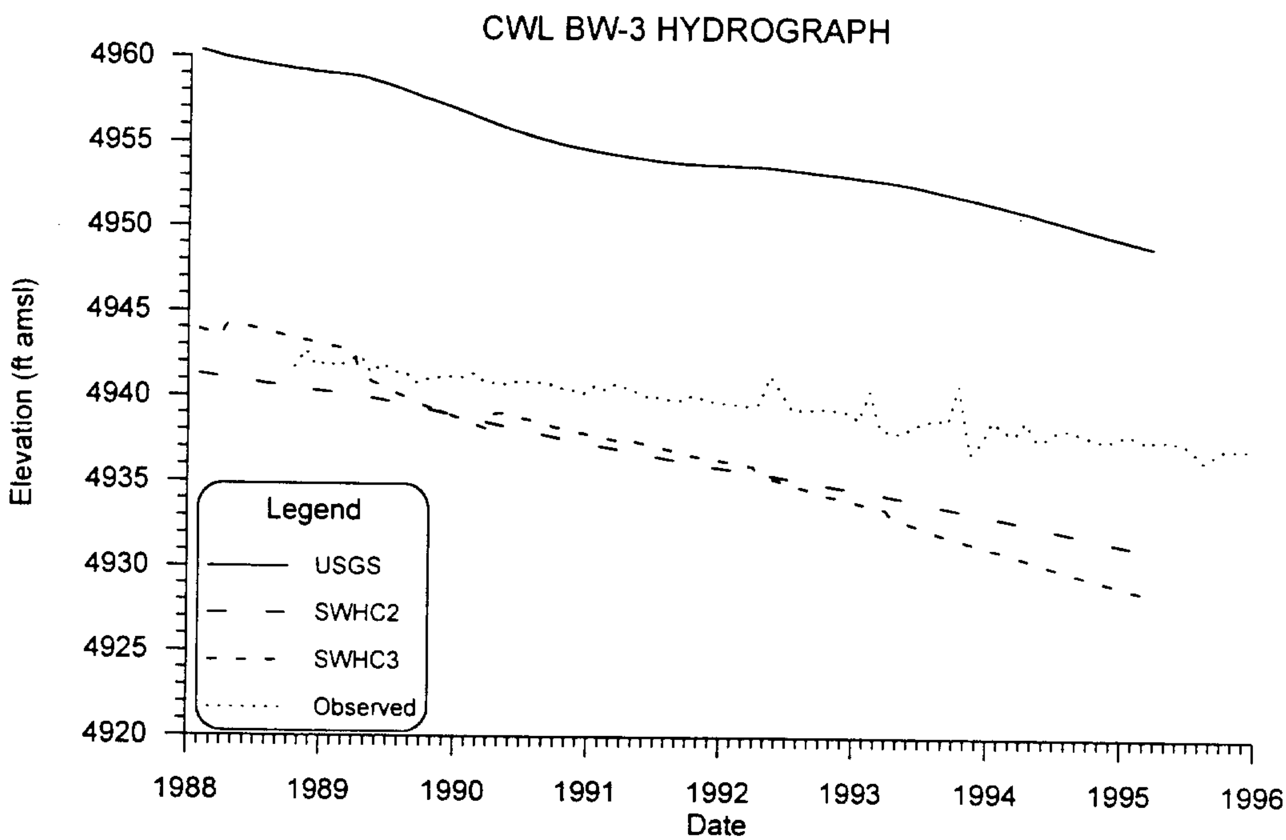
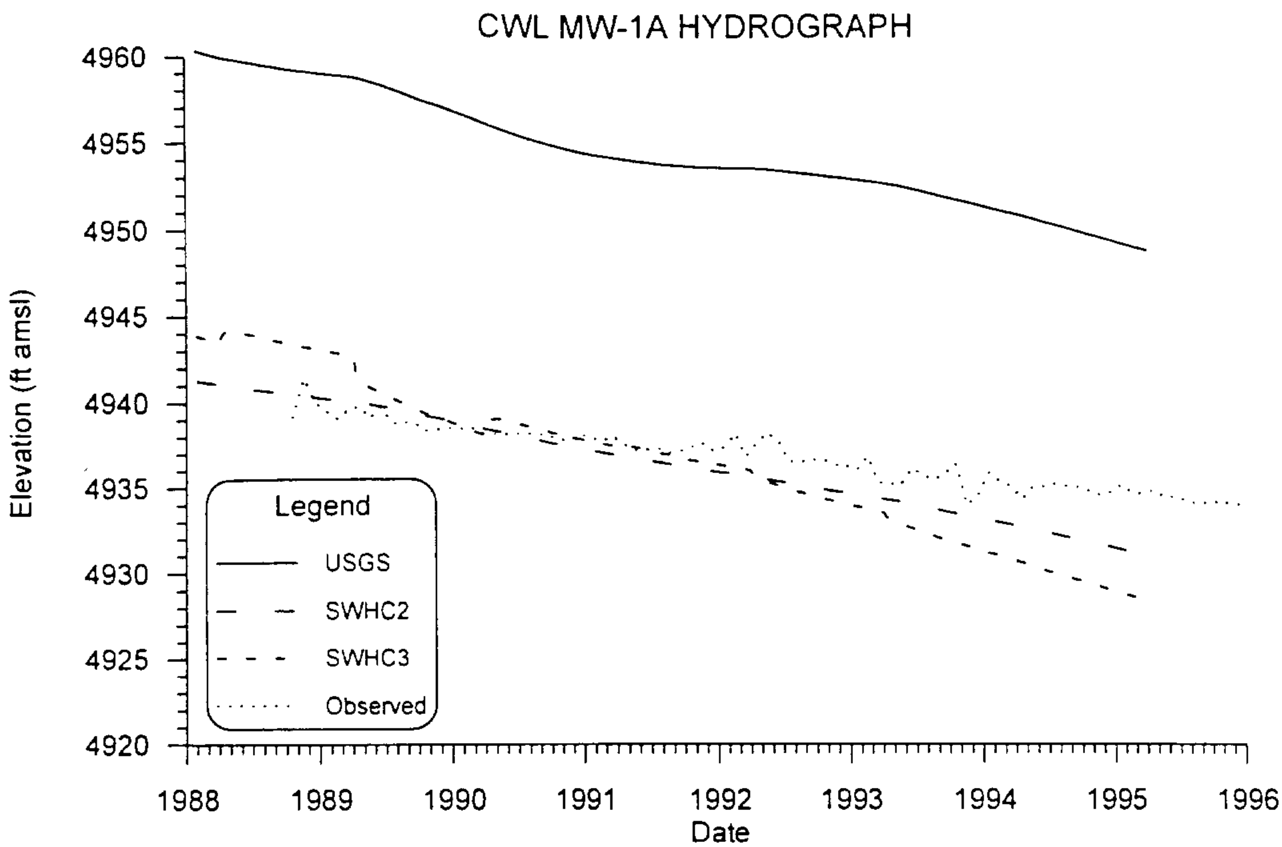
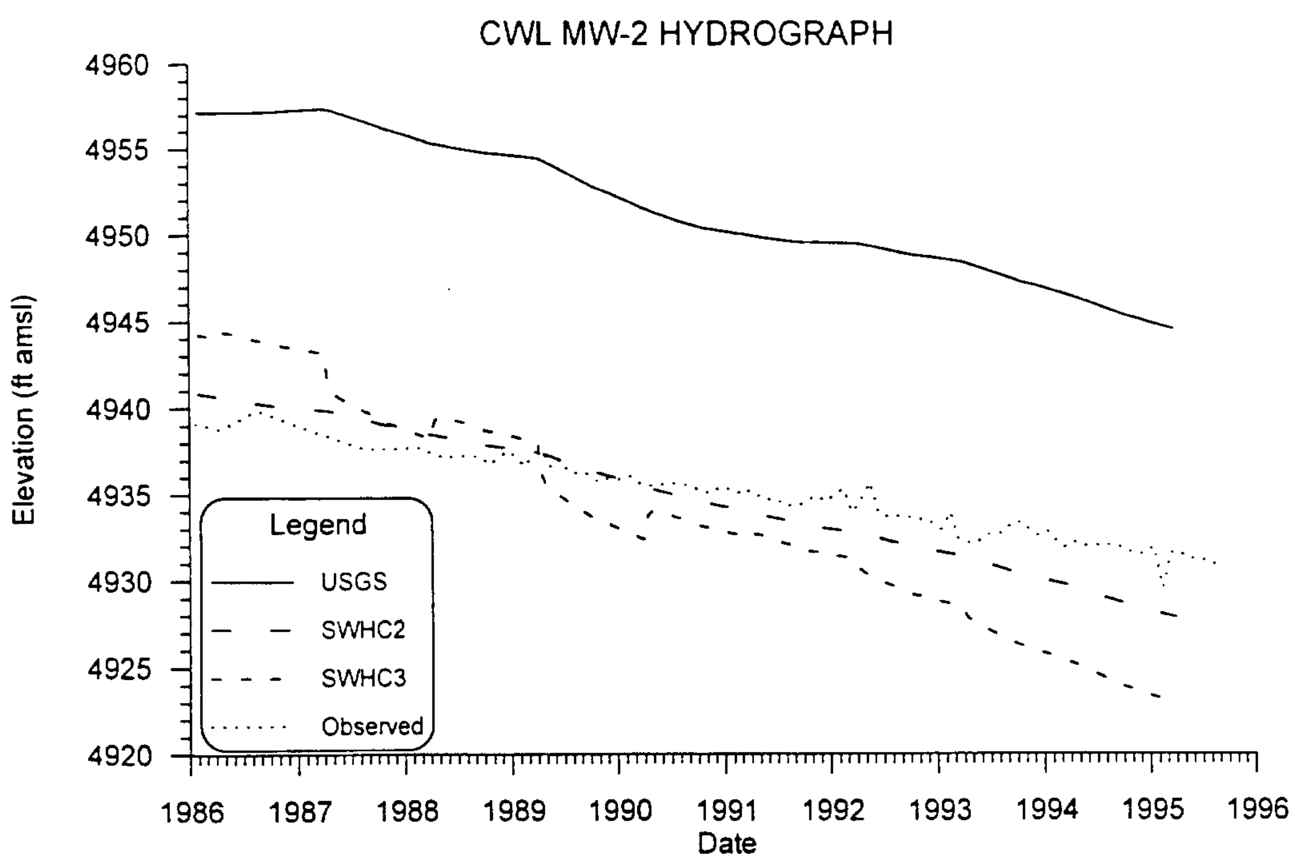
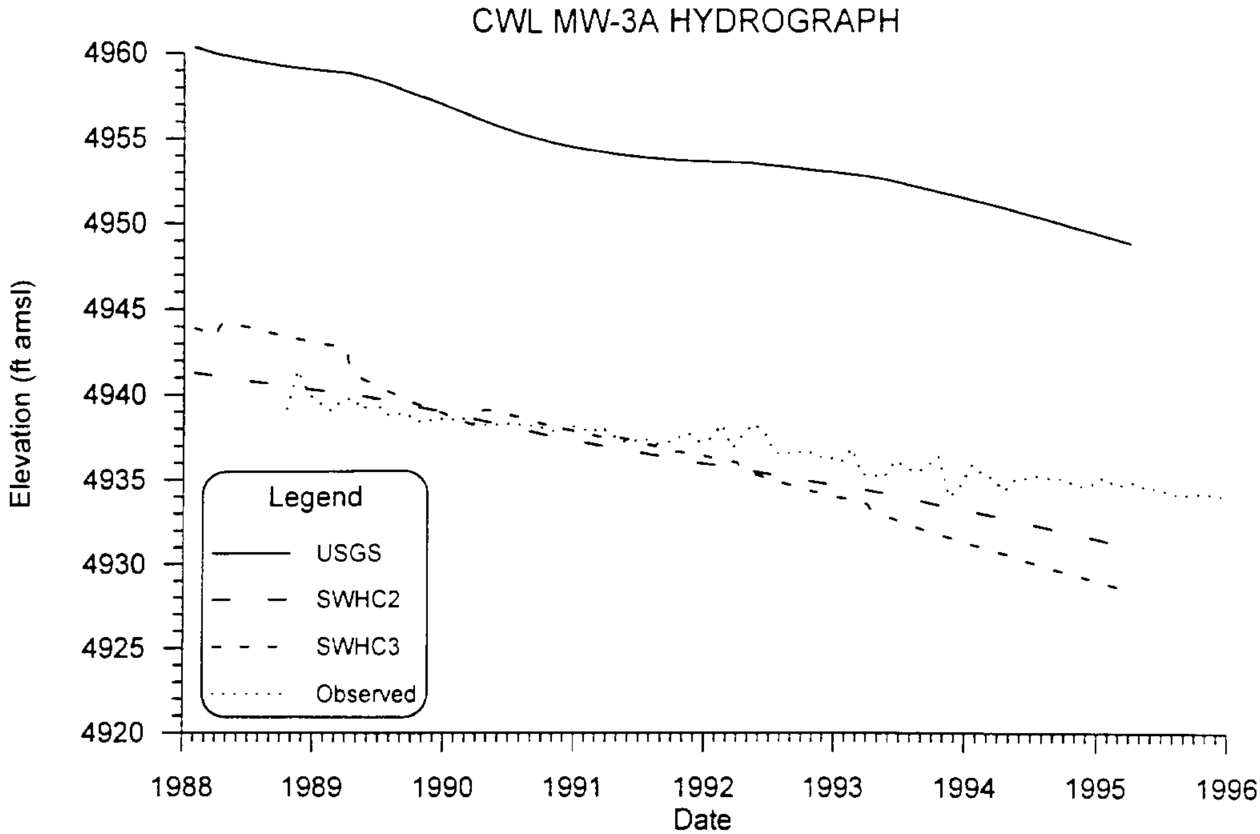
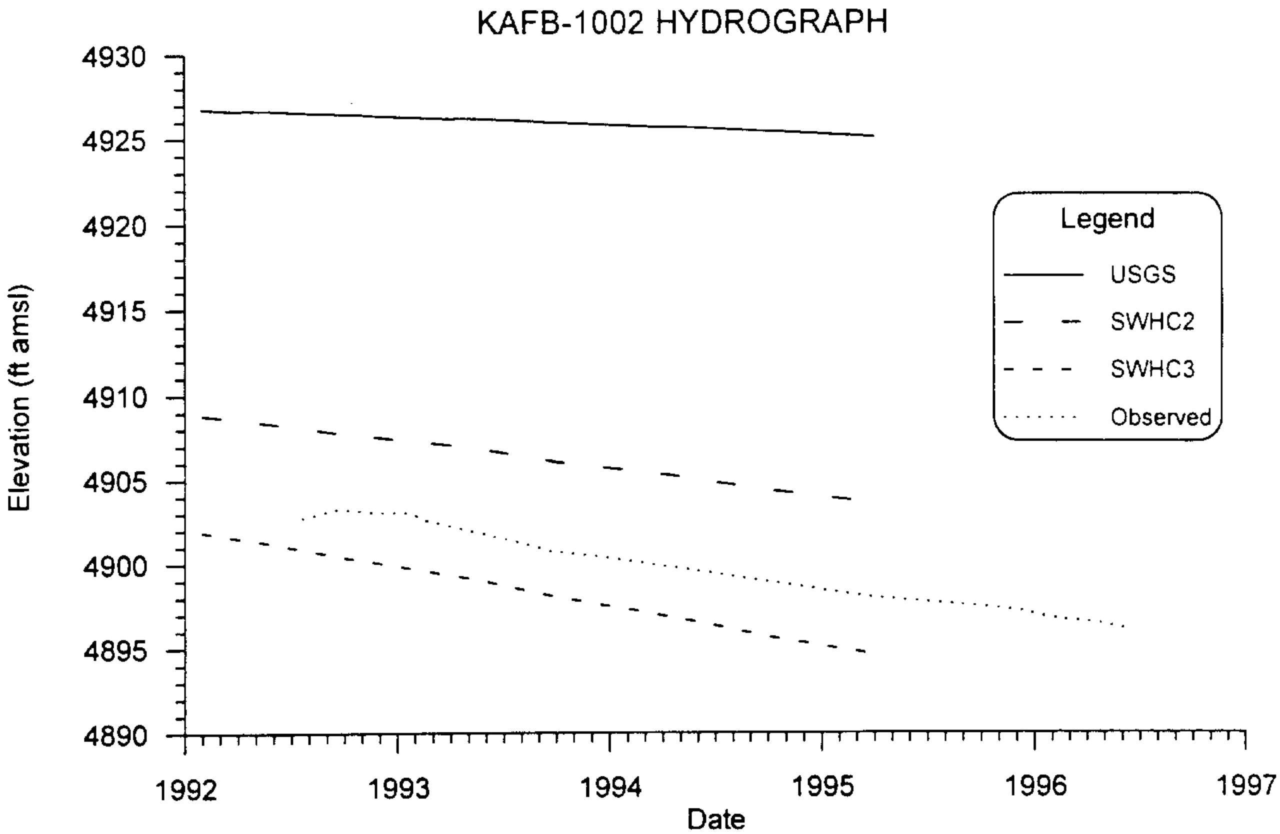

CHAVA HYDROGRAPH
Elevation (ft amsl)
4910
4905
4900
4895
Legend
USGS
SWHC2
SWHC3
Observed
1990
1991
1992
1993
1994
1995
1996
Date


CWL BW-3 HYDROGRAPH
Elevation (ft amsl)
4960
4955
4950
4945
4940
4935
4930
4925
4920
Legend
USGS
SWHC2
SWHC3
Observed
1988
1989
1990
1991
1992
1993
1994
1995
1996
Date

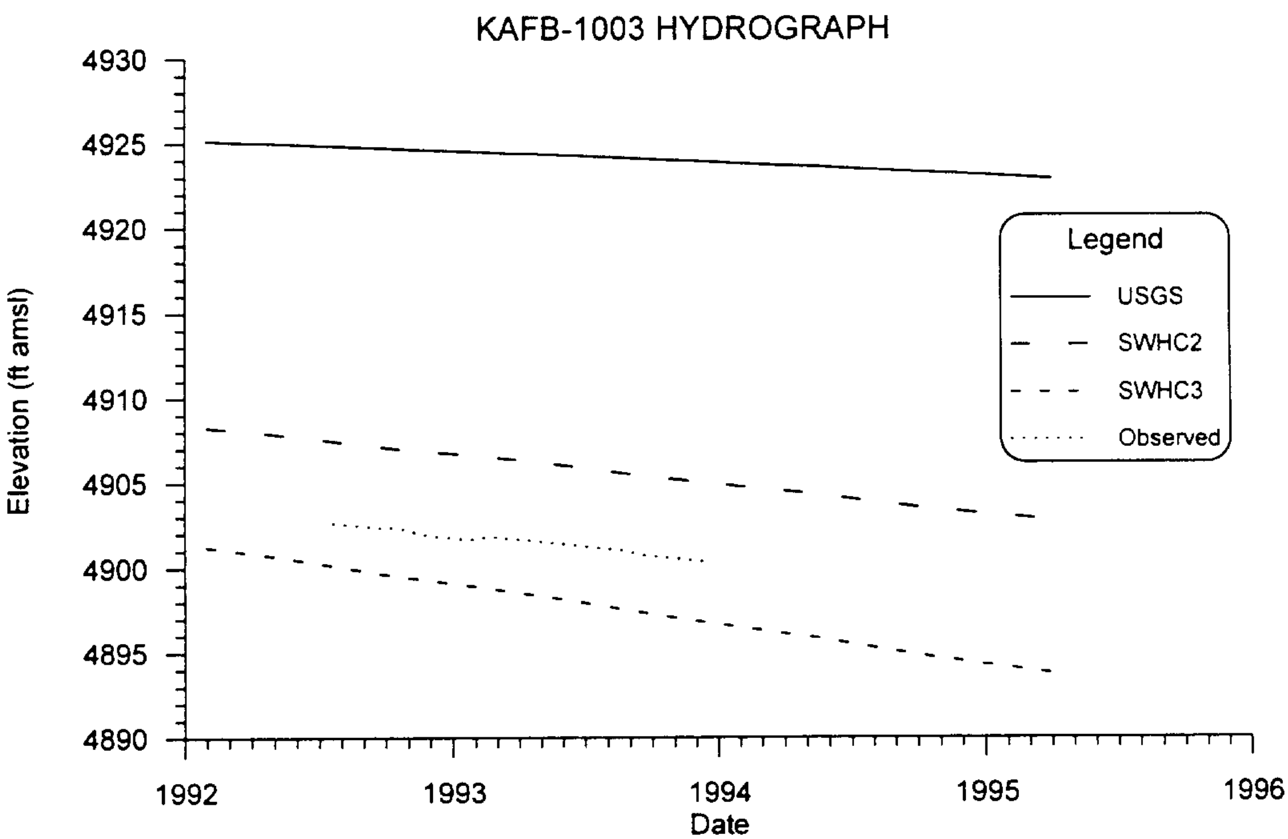

CWL MW-1A HYDROGRAPH
Elevation (ft amsl)
4960
4955
4950
4945
4940
4935
4930
4925
4920
1988
1989
1990
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed


CWL MW-2 HYDROGRAPH
Elevation (ft amsl)
4960
4955
4950
4945
4940
4935
4930
4925
4920
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

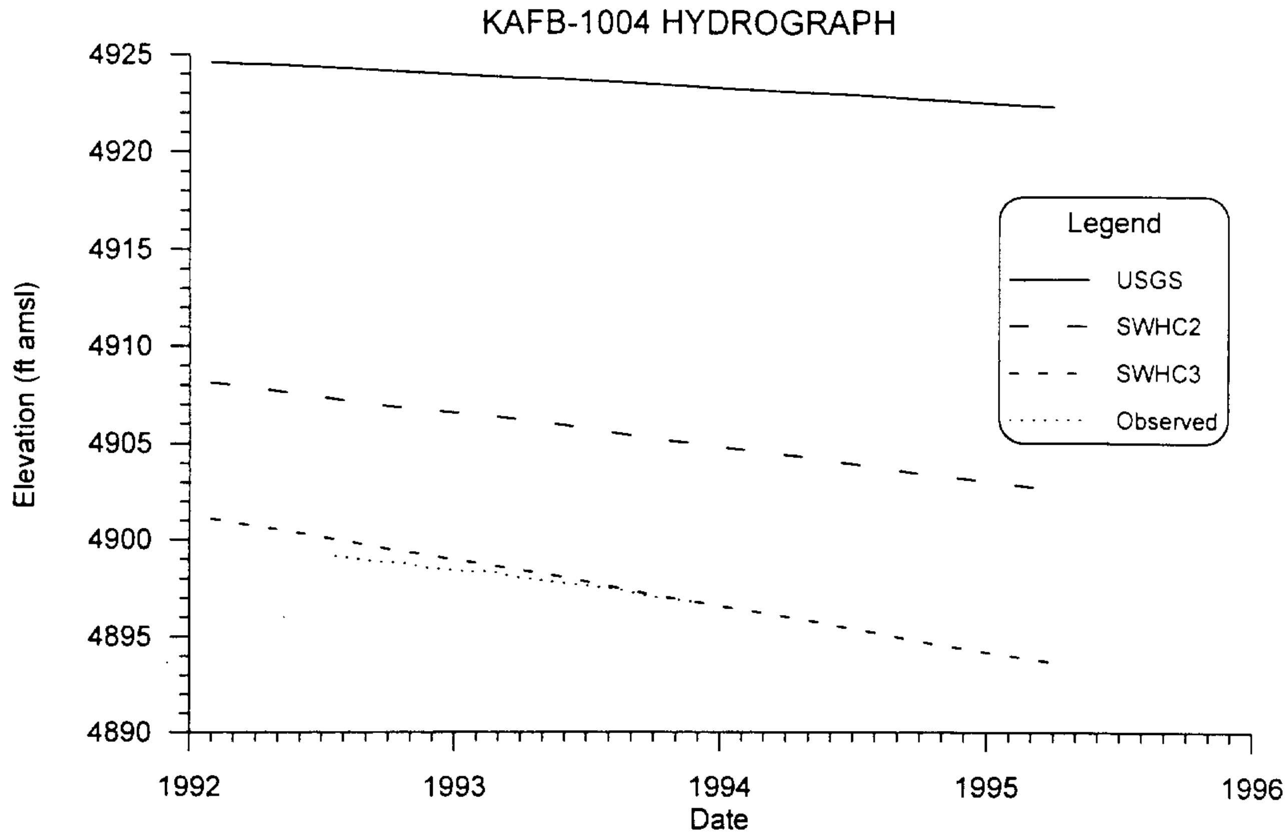

CWL MW-3A HYDROGRAPH
Elevation (ft amsl)
4960
4955
4950
4945
4940
4935
4930
4925
4920
Legend
USGS
SWHC2
SWHC3
Observed
1988
1989
1990
1991
1992
1993
1994
1995
1996
Date

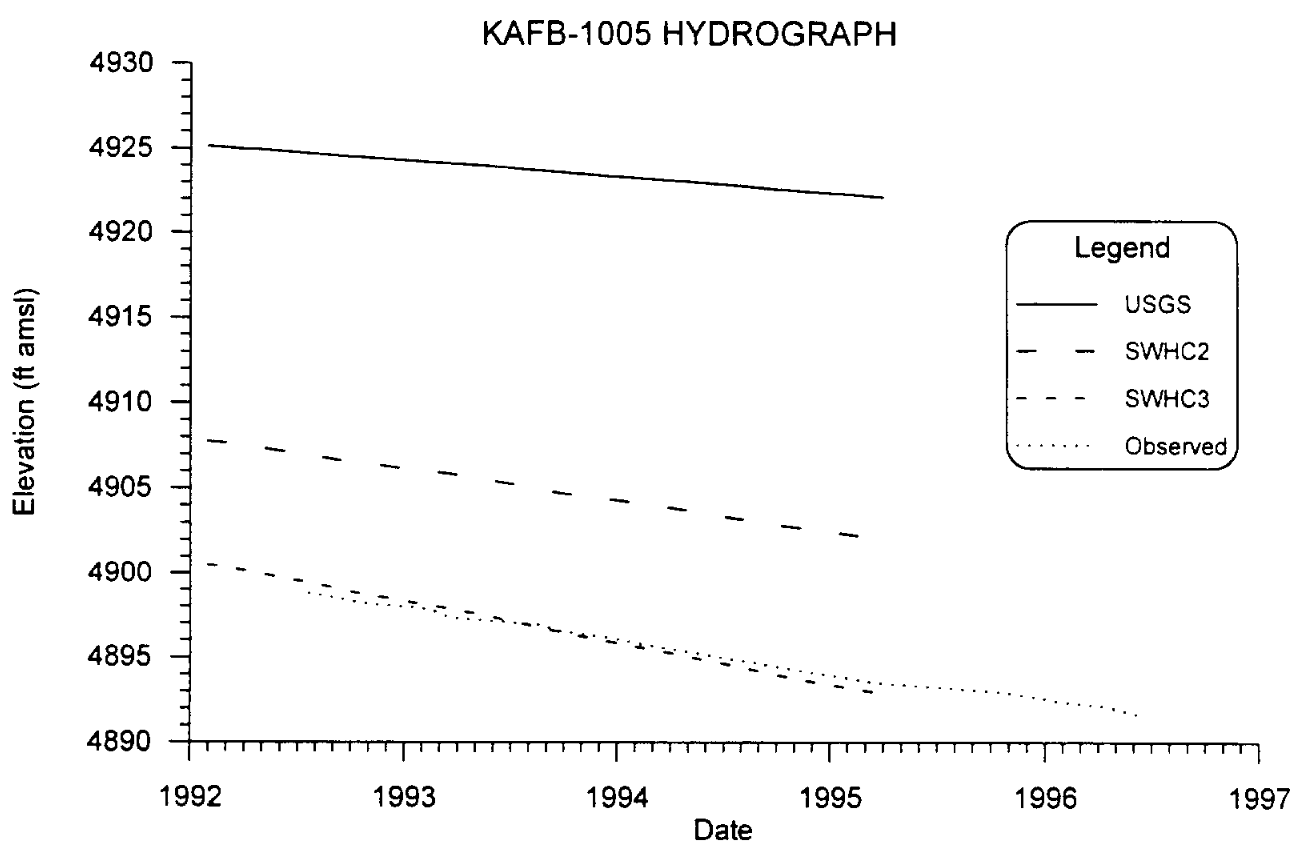


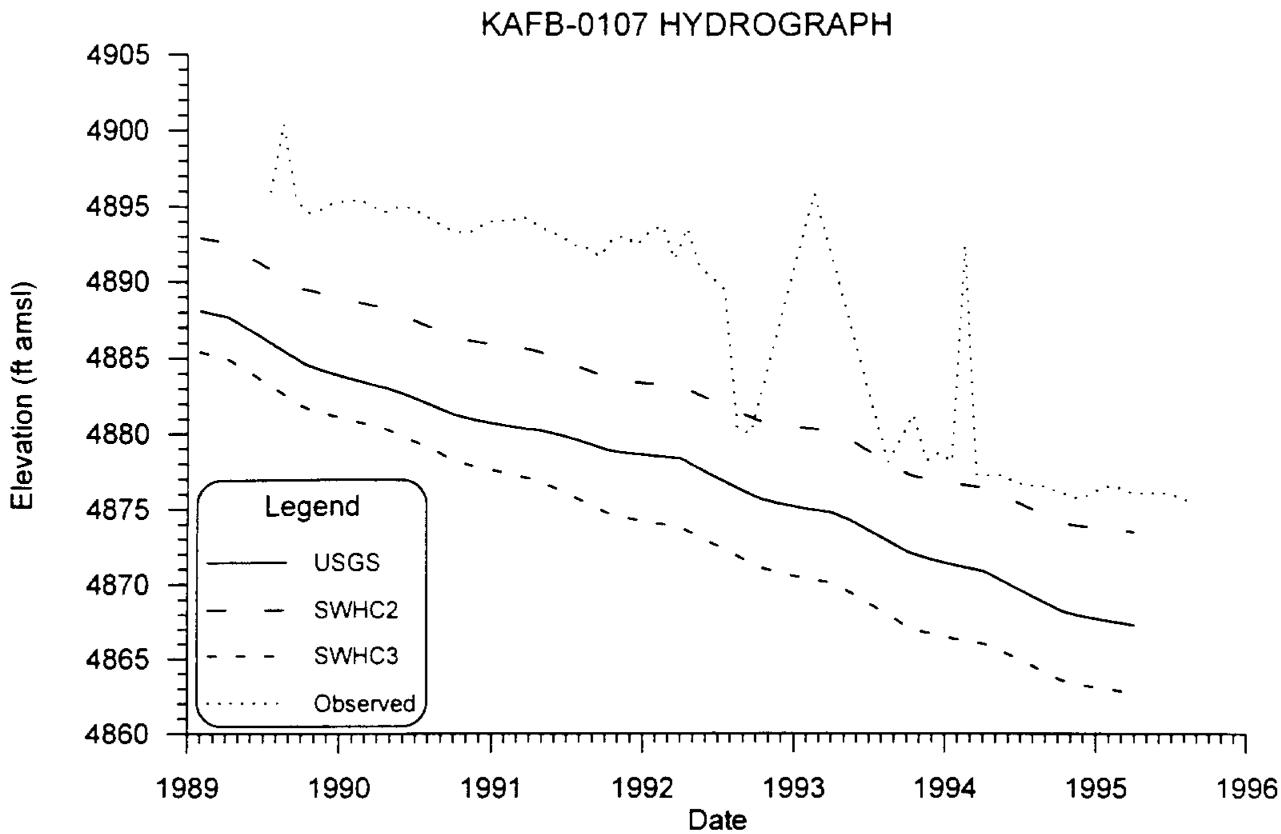
KAFB-1002 HYDROGRAPH
Elevation (ft amsl)
Date
Legend
USGS
SWHC2
SWHC3
Observed
4930
4925
4920
4915
4910
4905
4900
4895
4890
1992
1993
1994
1995
1996
1997

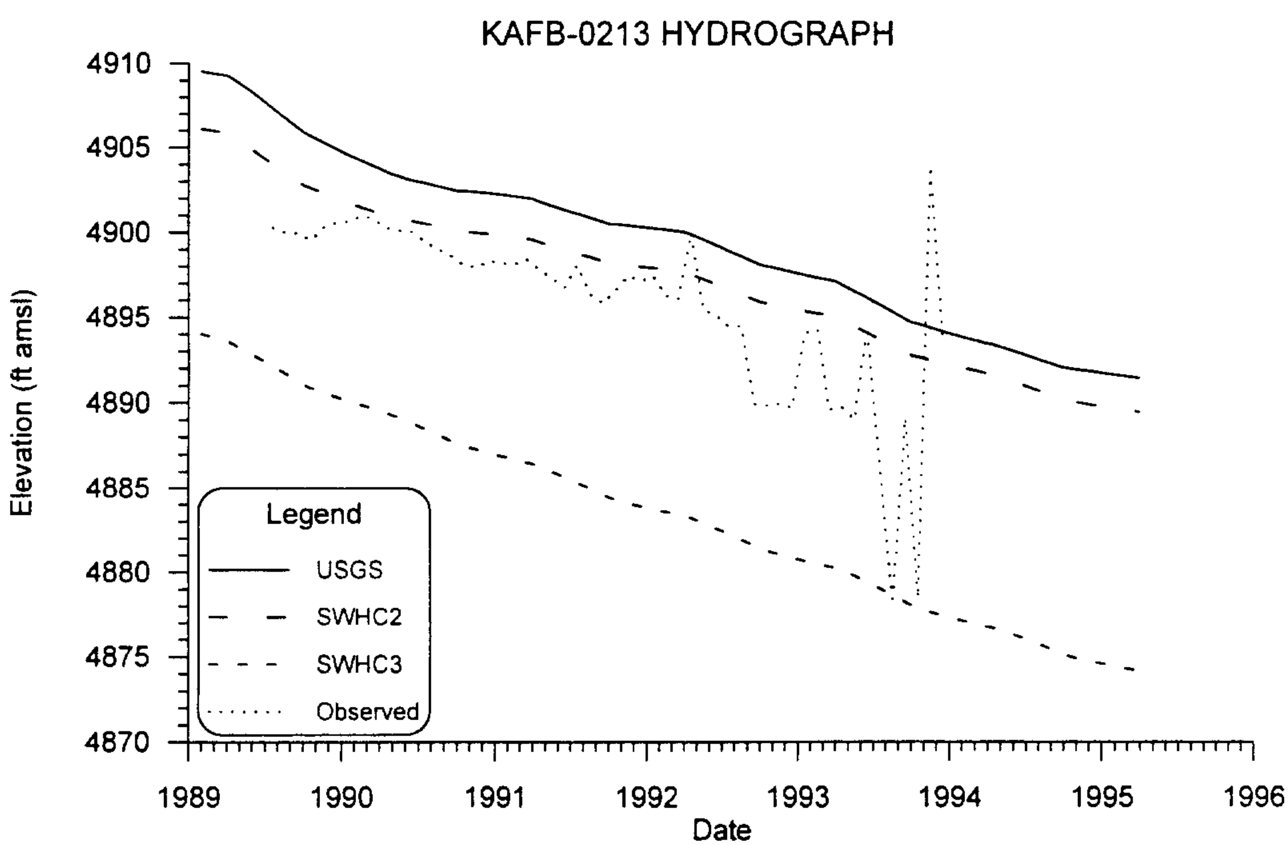


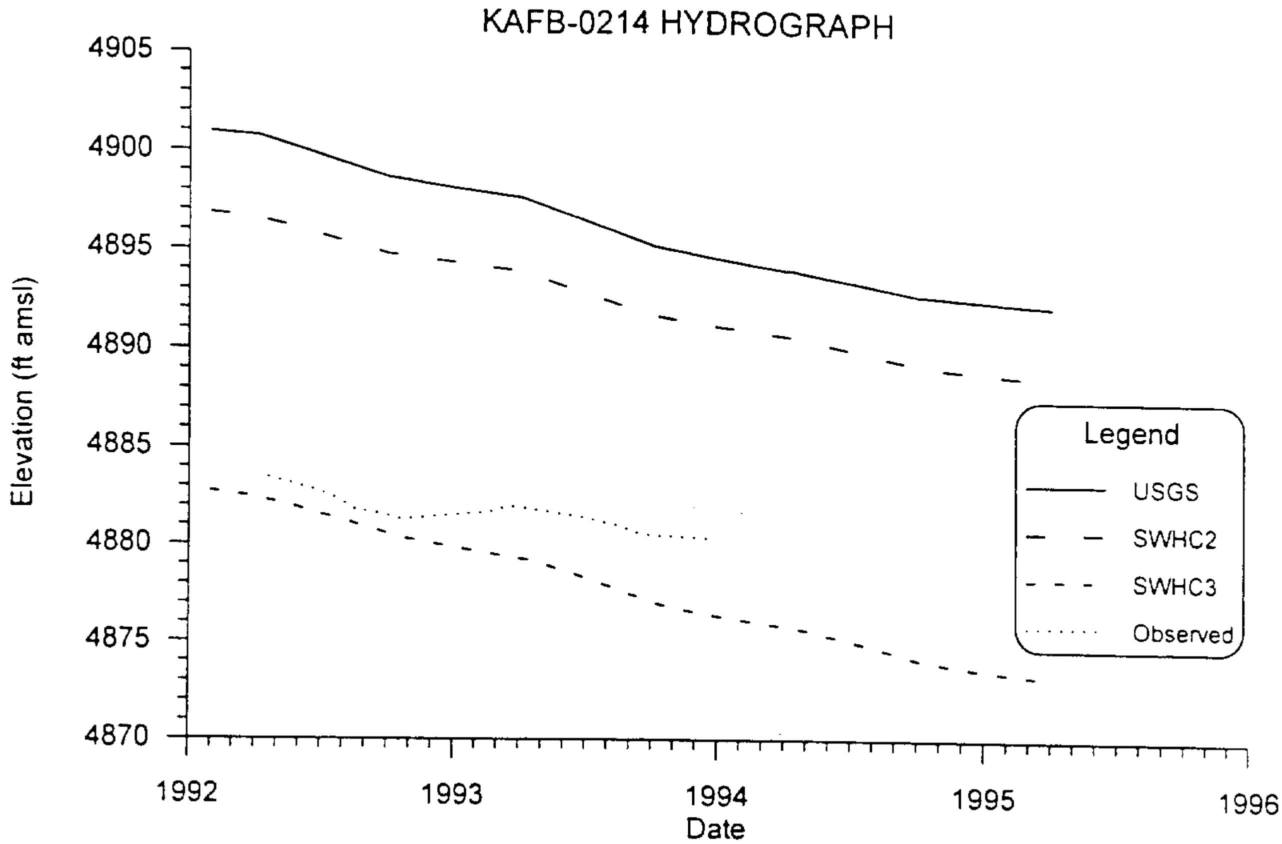
KAFB-1003 HYDROGRAPH
Elevation (ft amsl)
Date
Legend
USGS
SWHC2
SWHC3
Observed
4930
4925
4920
4915
4910
4905
4900
4895
4890
1992
1993
1994
1995
1996

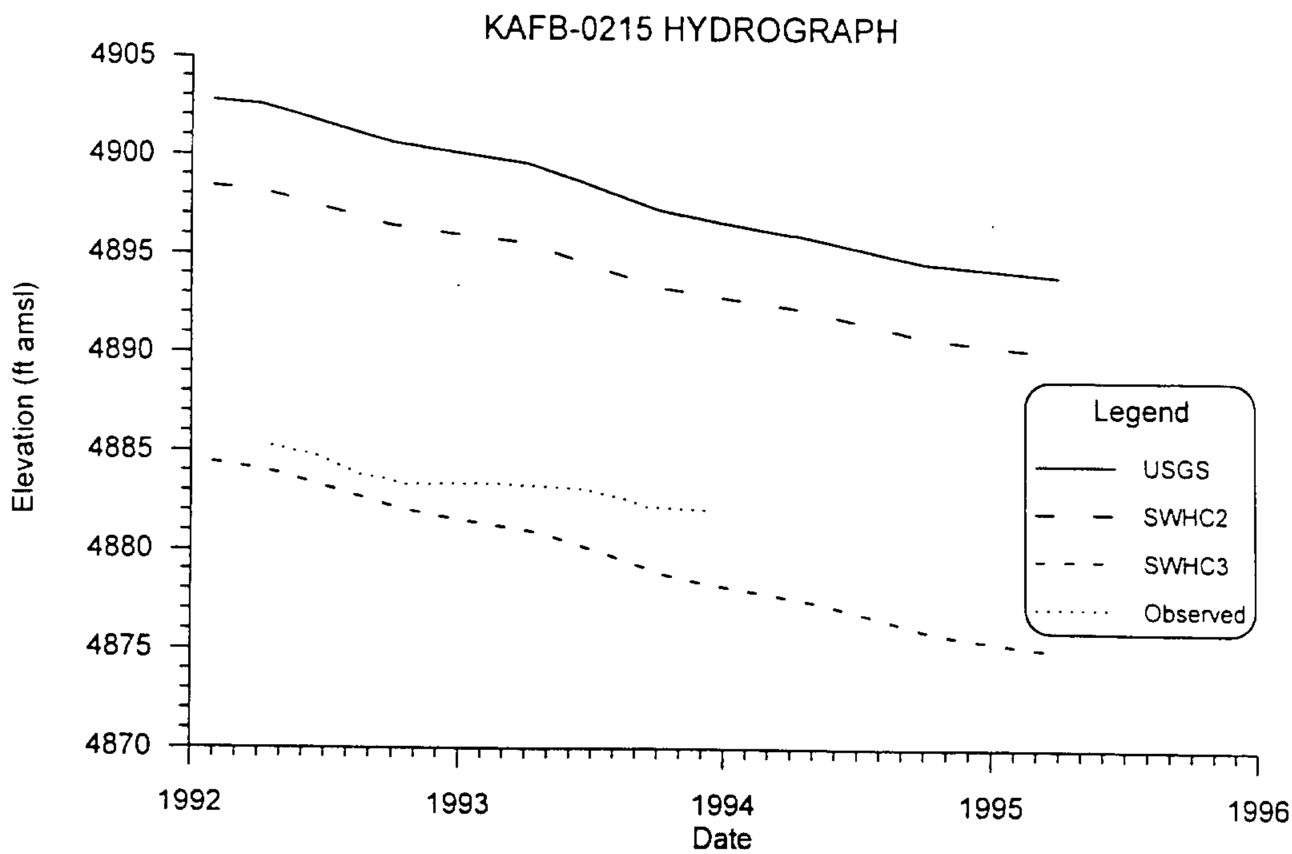

KAFB-1004 HYDROGRAPH
Elevation (ft amsl)
Date
Legend
USGS
SWHC2
SWHC3
Observed
4925
4920
4915
4910
4905
4900
4895
4890
1992
1993
1994
1995
1996

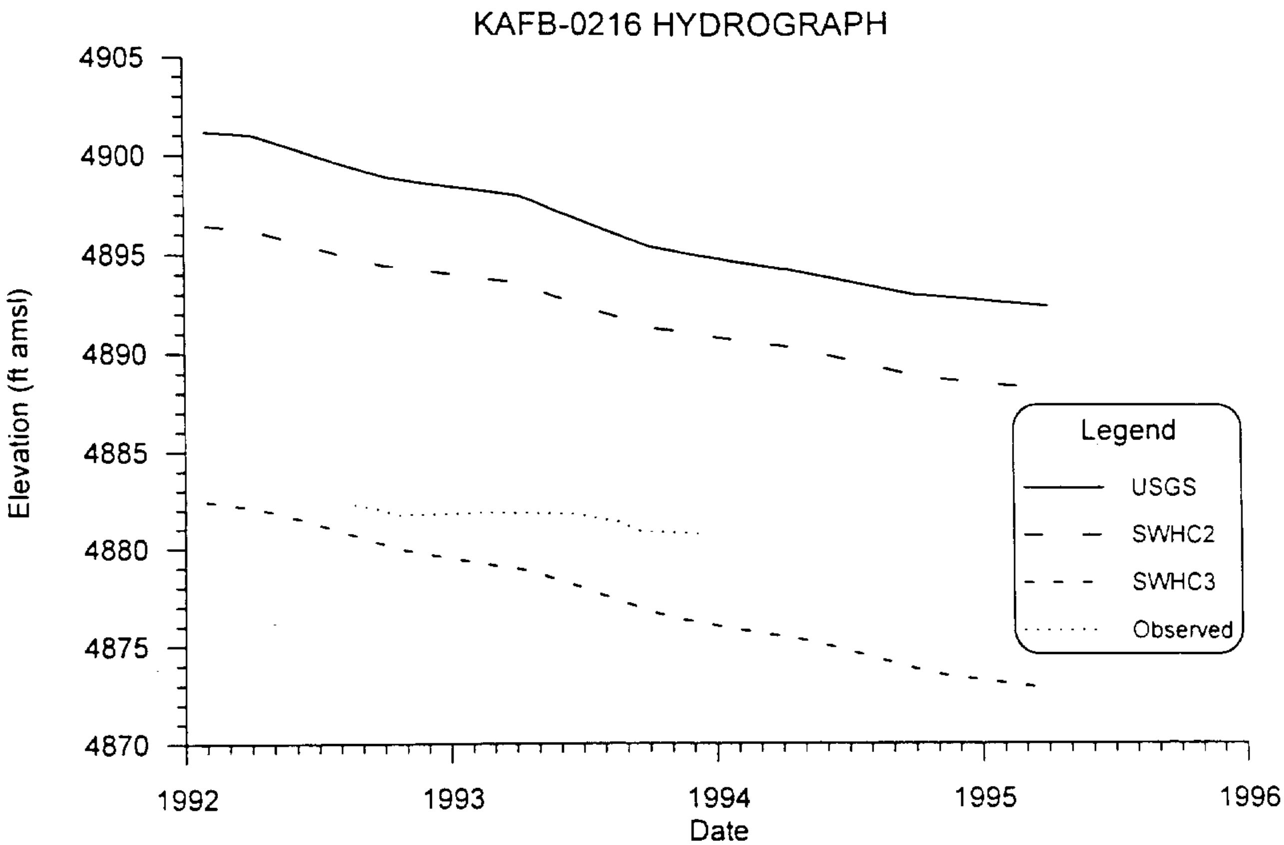

KAFB-1005 HYDROGRAPH
Elevation (ft amsl)
Date
Legend
USGS
SWHC2
SWHC3
Observed
4930
4925
4920
4915
4910
4905
4900
4895
4890
1992
1993
1994
1995
1996
1997

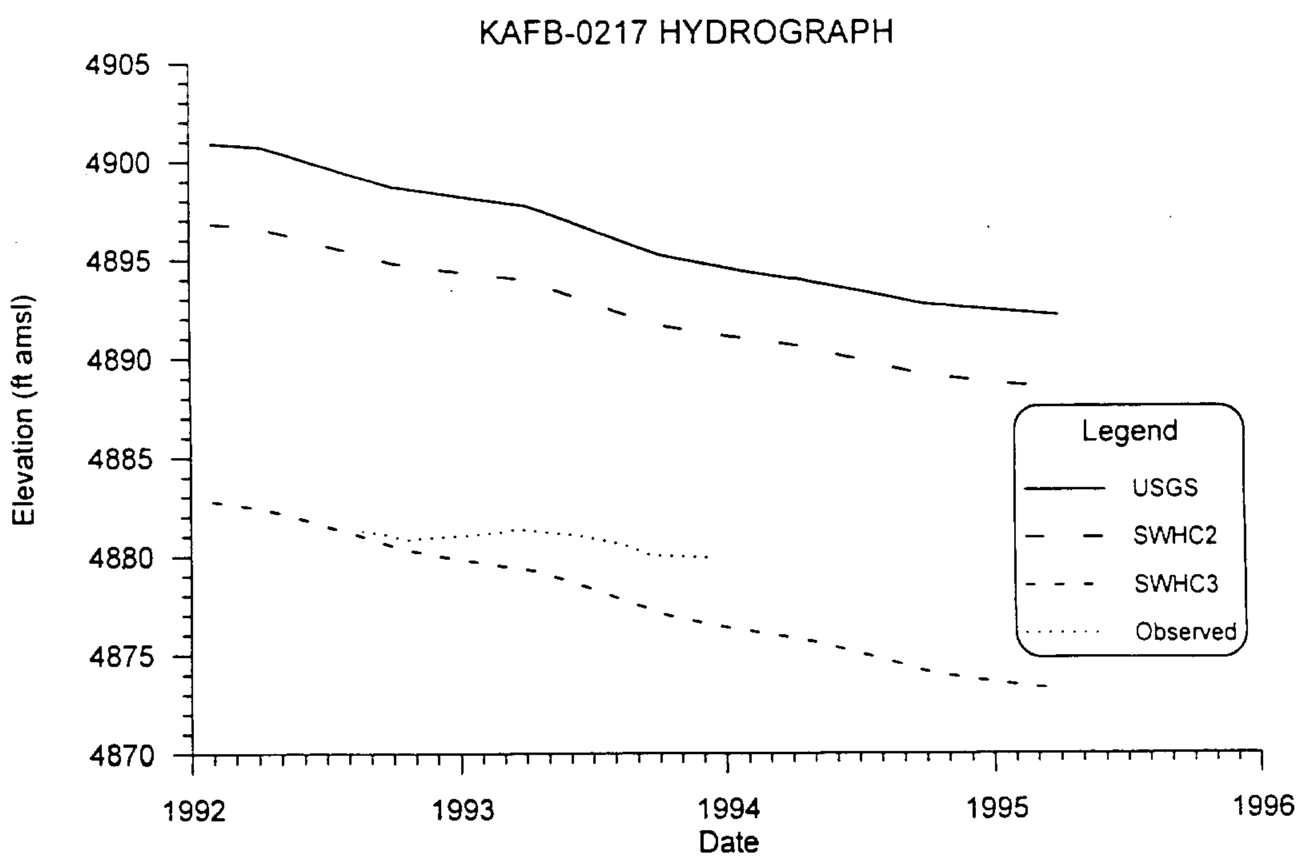

KAFB-0107 HYDROGRAPH
4905
4900
4895
4890
4885
4880
4875
4870
4865
4860
Elevation (ft amsl)
1989
1990
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

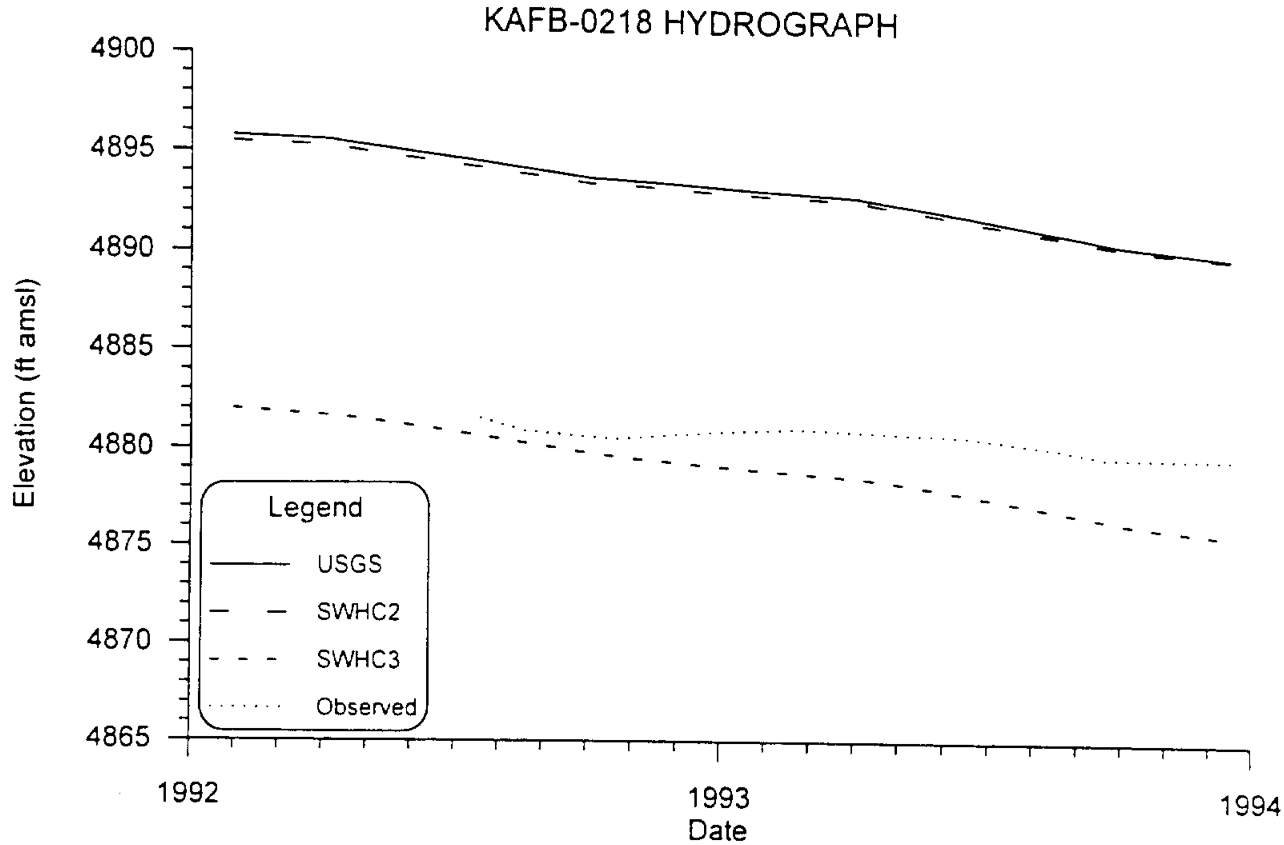

KAFB-0213 HYDROGRAPH
4910
4905
4900
4895
4890
4885
4880
4875
4870
Elevation (ft amsl)
1989
1990
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed


KAFB-0214 HYDROGRAPH
4905
4900
4895
4890
4885
4880
4875
4870
Elevation (ft amsl)
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

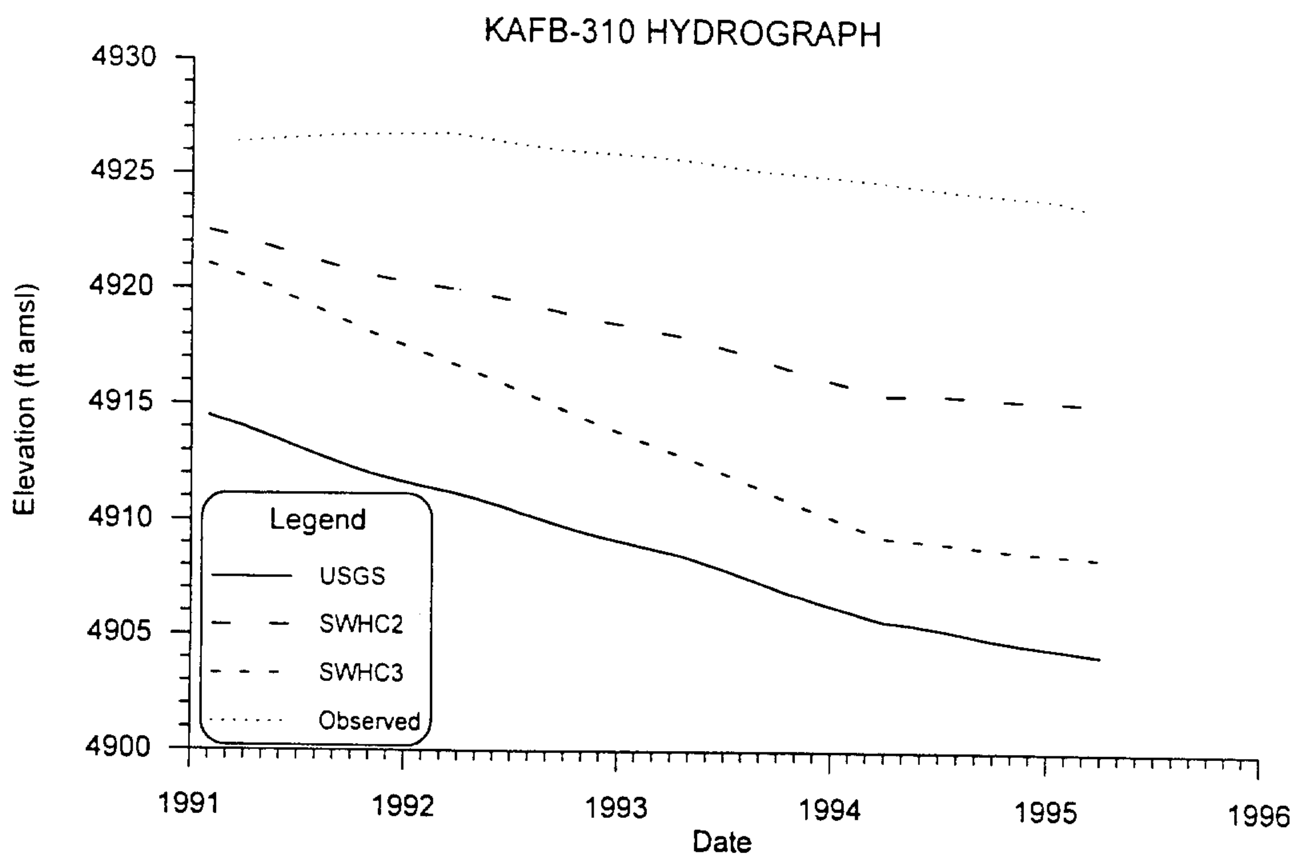

KAFB-0215 HYDROGRAPH
4905
4900
4895
4890
4885
4880
4875
4870
Elevation (ft amsl)
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed


KAFB-0216 HYDROGRAPH
4905
4900
4895
4890
4885
4880
4875
4870
Elevation (ft amsl)
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

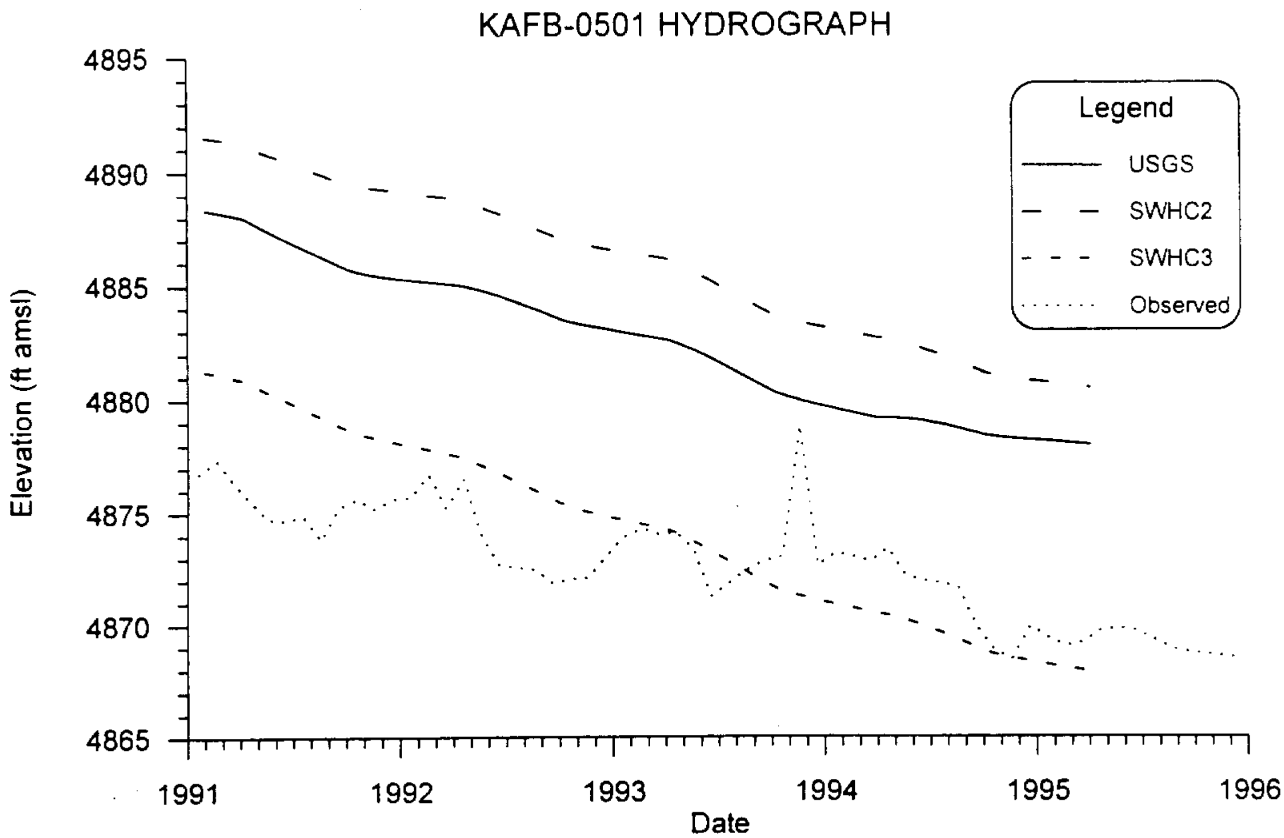

KAFB-0217 HYDROGRAPH
4905
4900
4895
4890
4885
4880
4875
4870
Elevation (ft amsl)
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

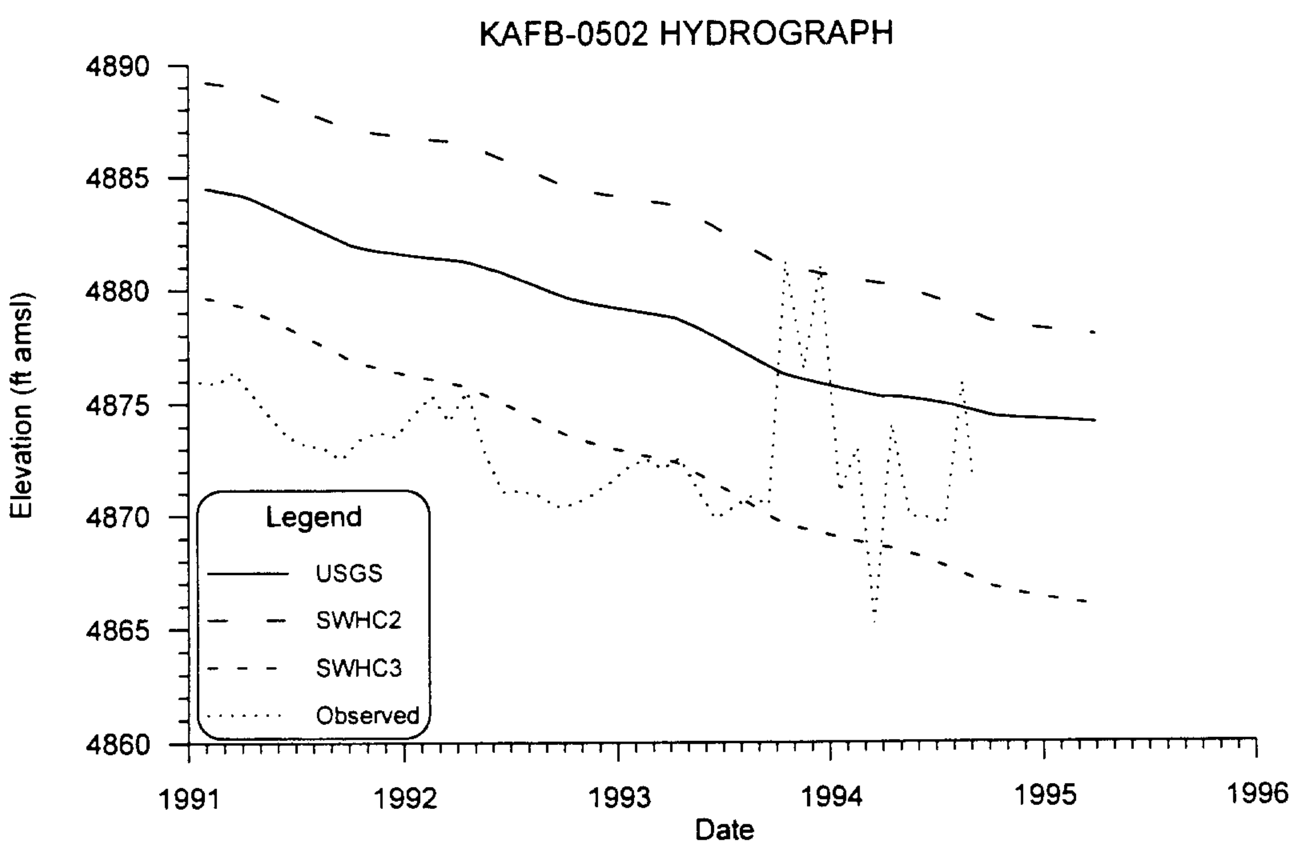


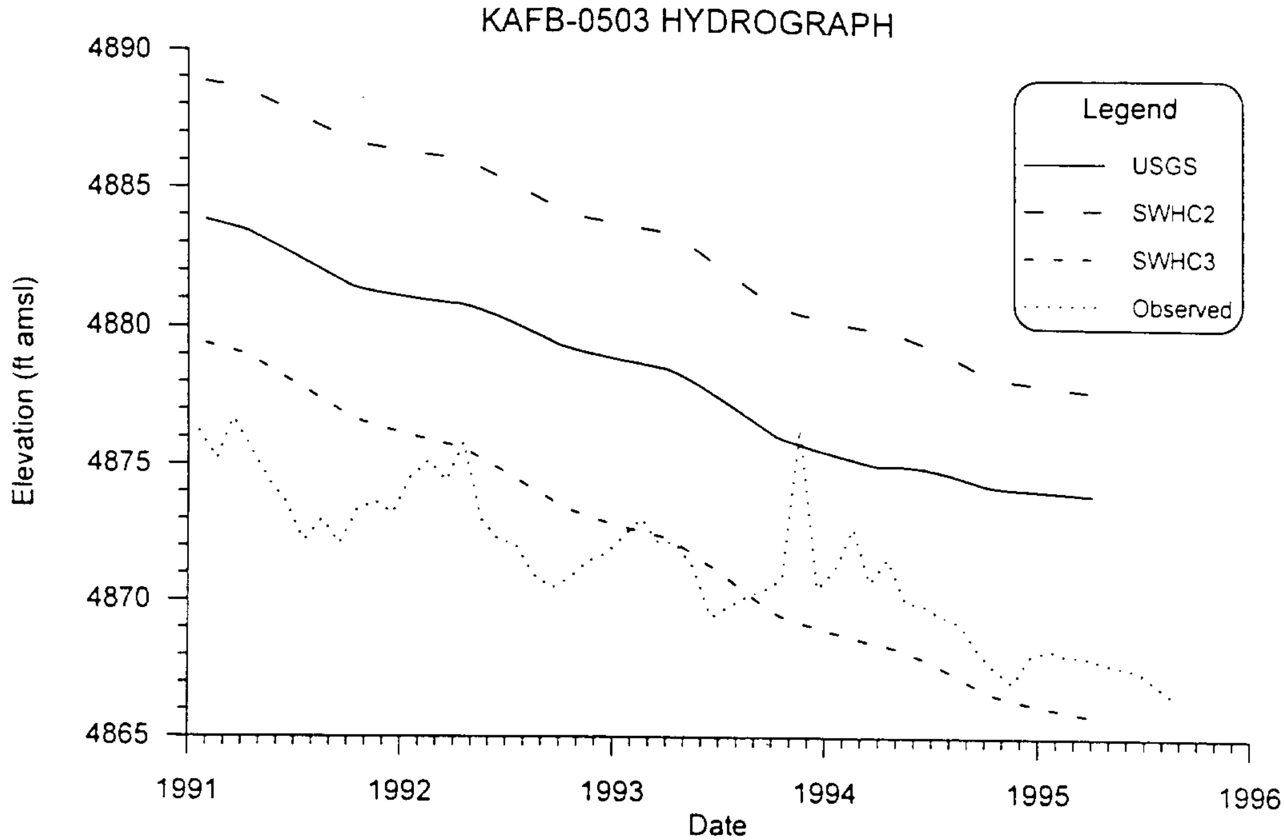
KAFB-0218 HYDROGRAPH
4900
4895
4890
4885
4880
4875
4870
4865
Elevation (ft amsl)
Legend
USGS
SWHC2
SWHC3
Observed
1992
1993
1994
Date

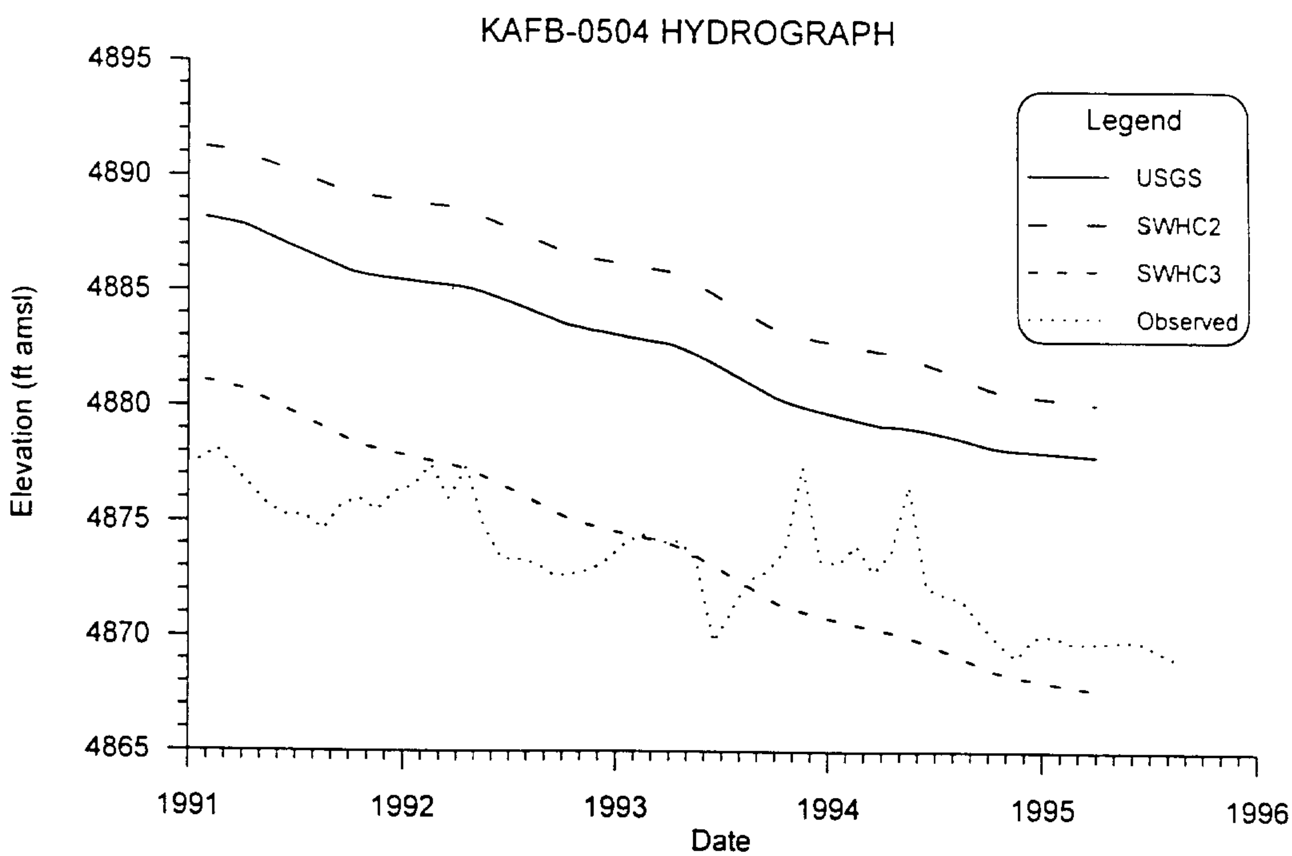


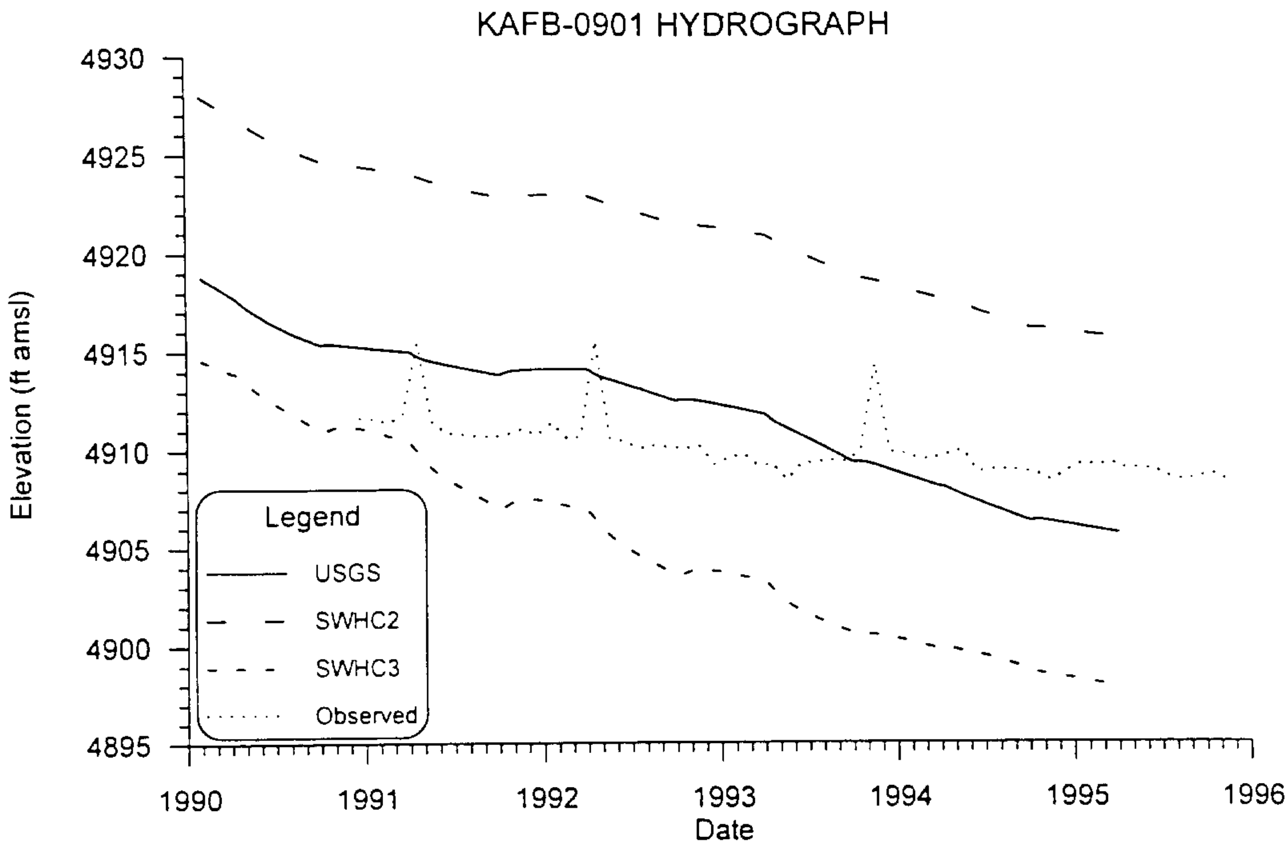
KAFB-310 HYDROGRAPH
4930
4925
4920
4915
4910
4905
4900
Elevation (ft amsl)
Legend
USGS
SWHC2
SWHC3
Observed
1991
1992
1993
1994
1995
1996
Date

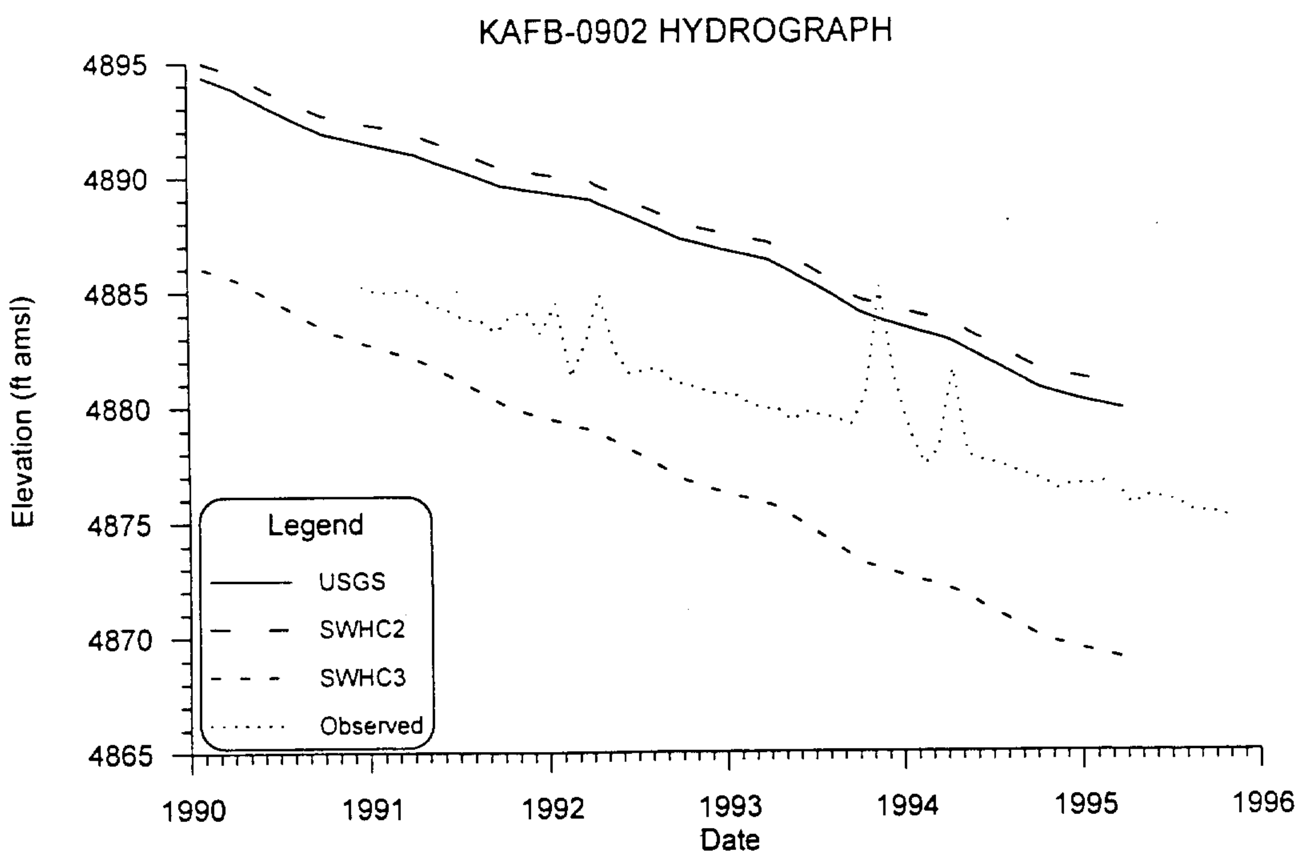

KAFB-0501 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4895
4890
4885
4880
4875
4870
4865
1991
1992
1993
1994
1995
1996
Date

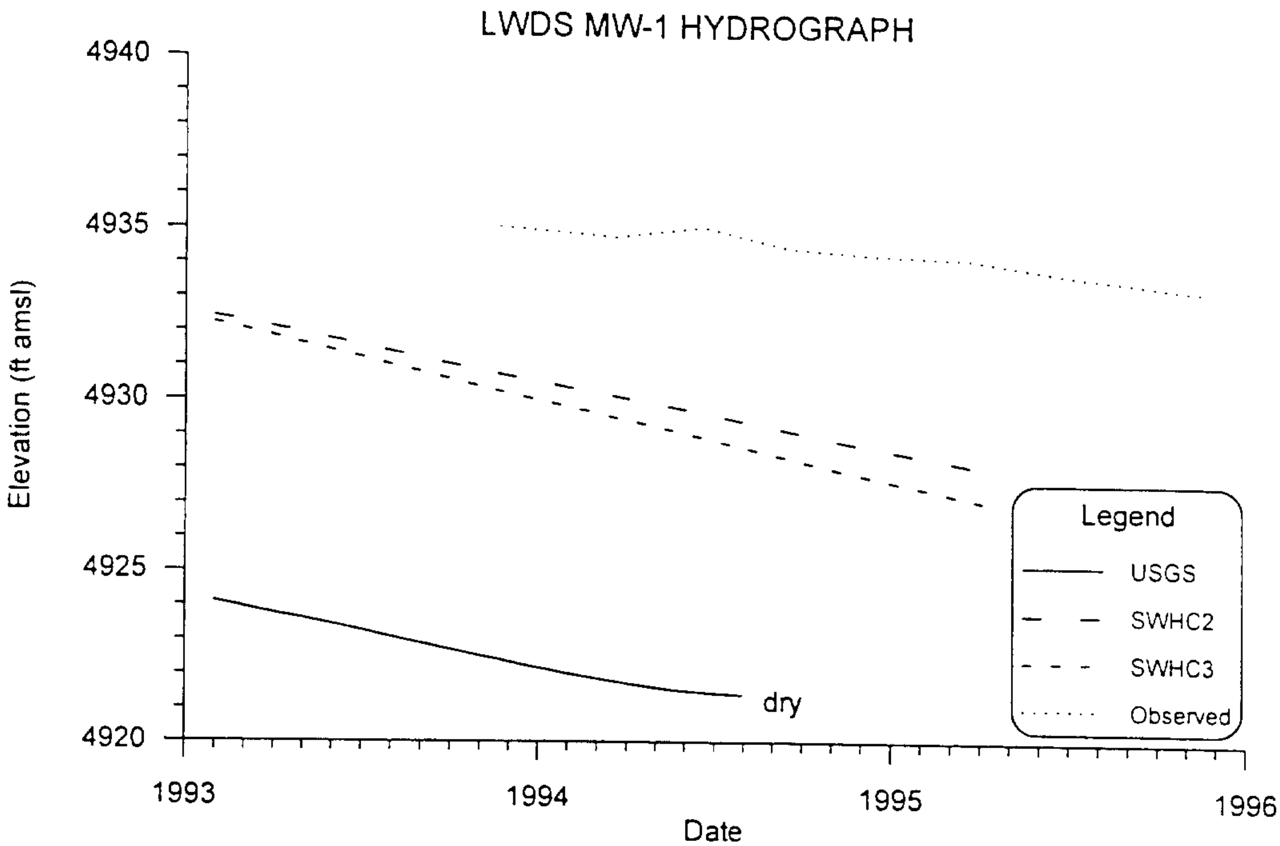

KAFB-0502 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4890
4885
4880
4875
4870
4865
4860
1991
1992
1993
1994
1995
1996
Date

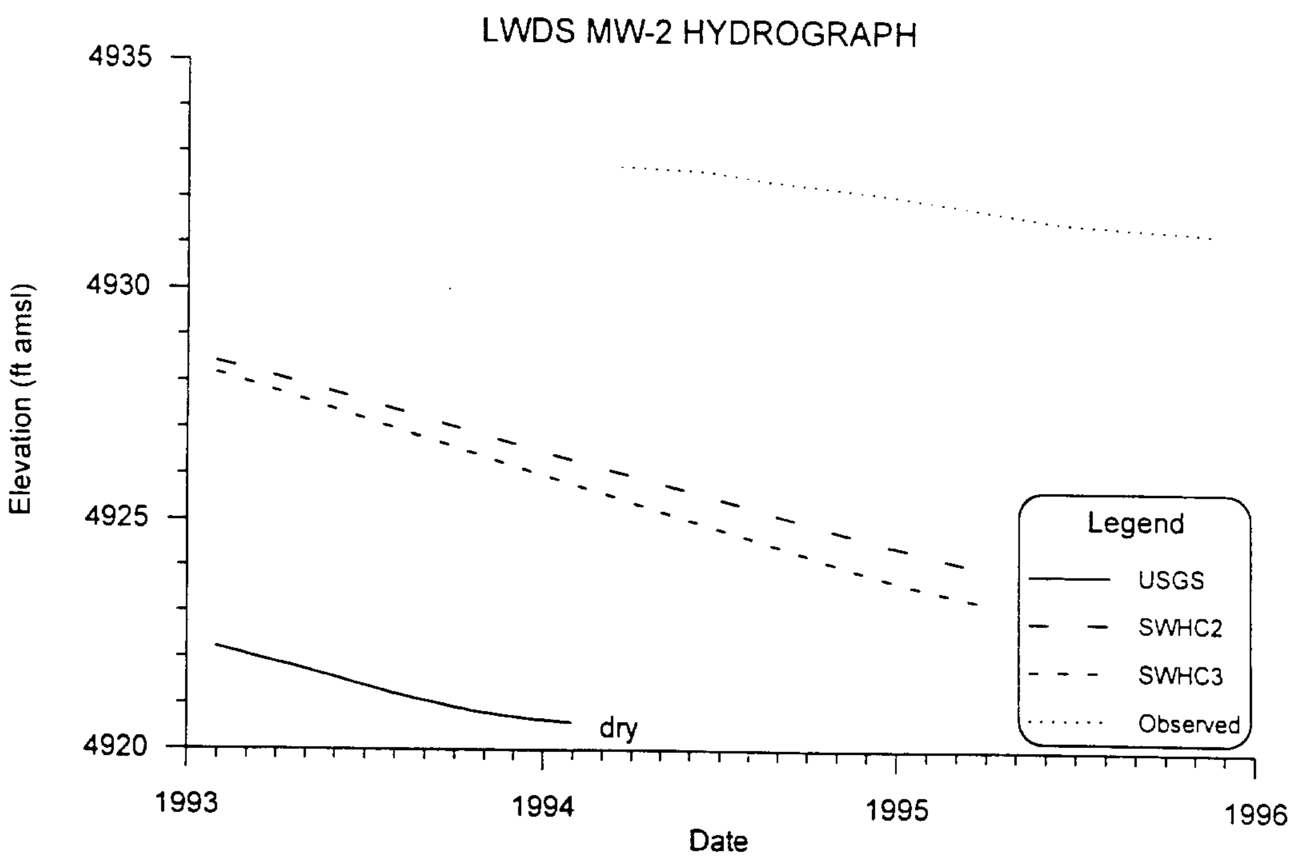

KAFB-0503 HYDROGRAPH
4890
4885
4880
4875
4870
4865
Elevation (ft amsl)
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

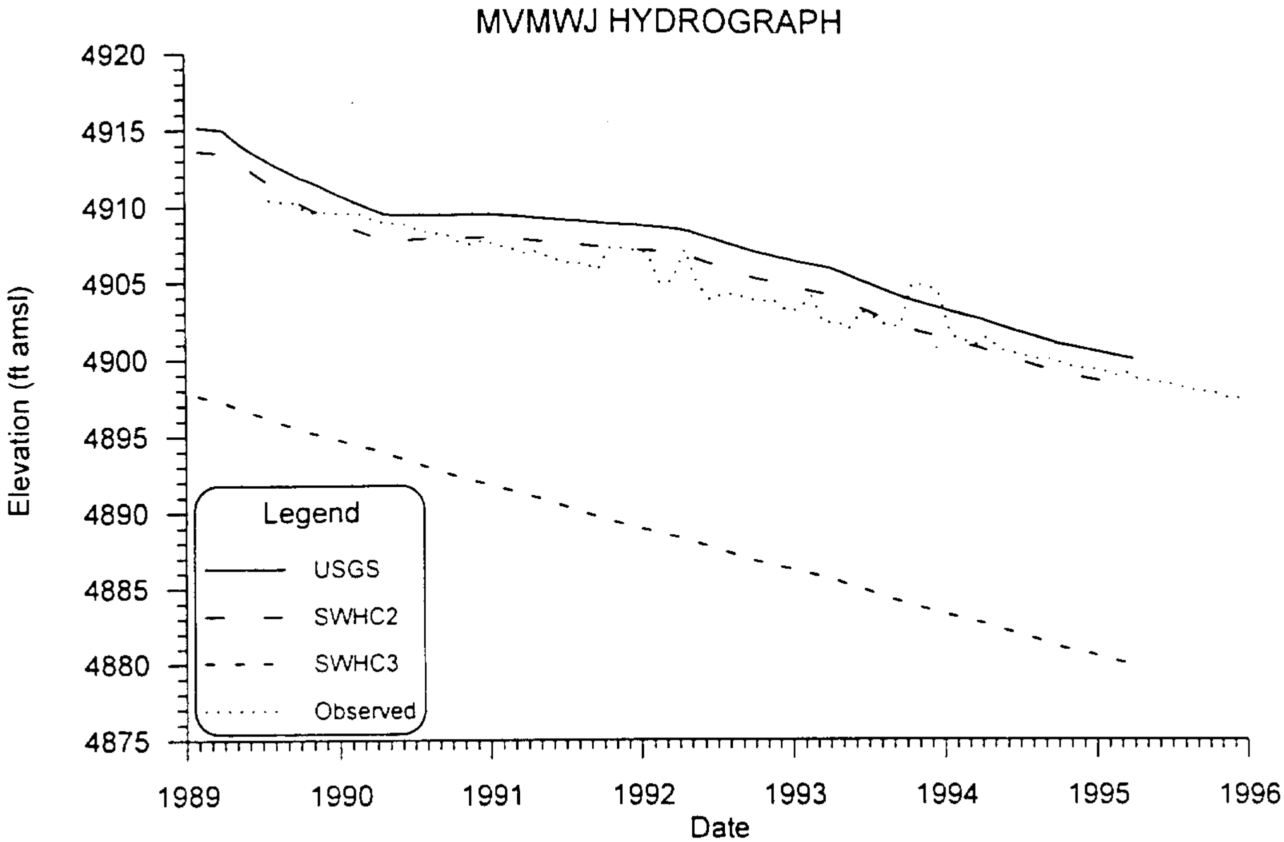

KAFB-0504 HYDROGRAPH
4895
4890
4885
4880
4875
4870
4865
Elevation (ft amsl)
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed


KAFB-0901 HYDROGRAPH
4930
4925
4920
4915
4910
4905
4900
4895
Elevation (ft amsl)
1990
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

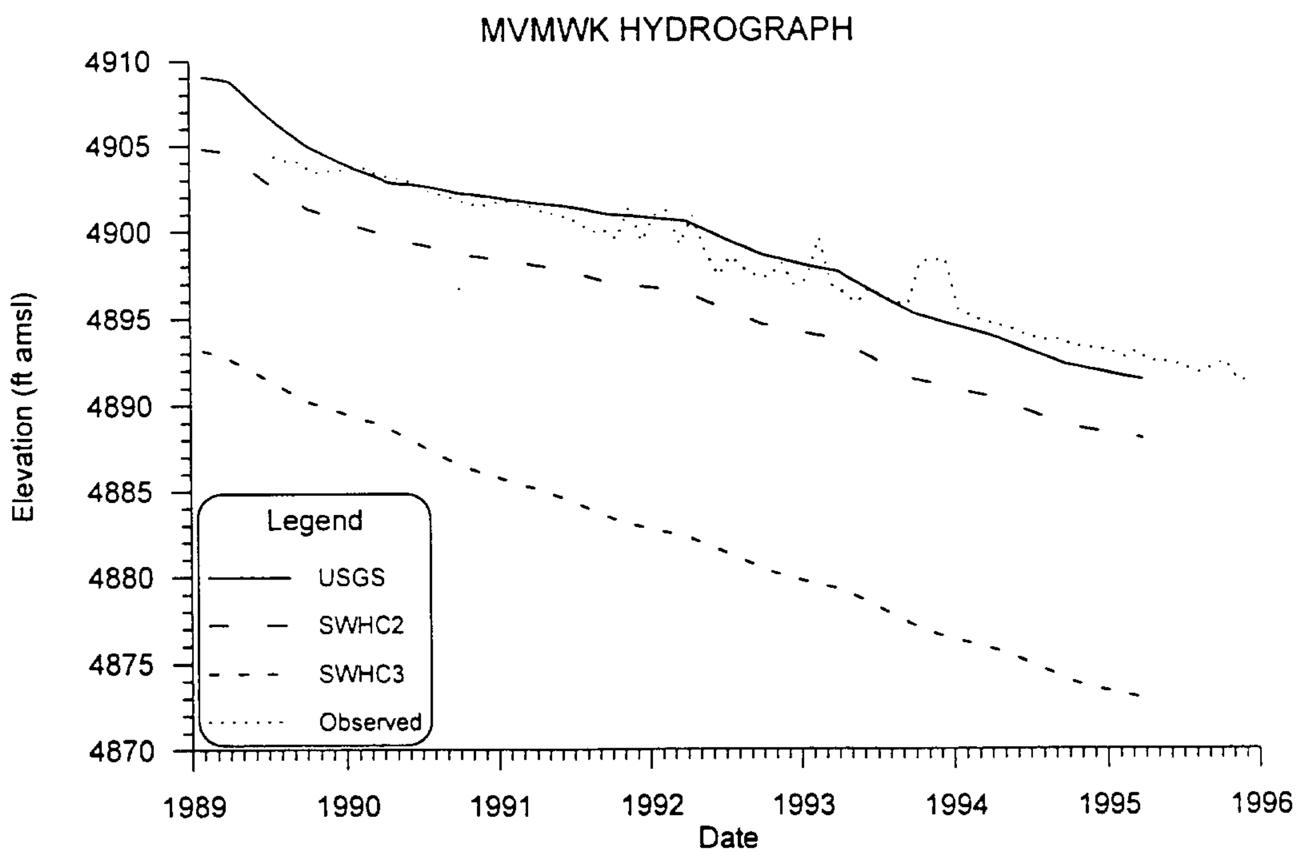

KAFB-0902 HYDROGRAPH
4895
4890
4885
4880
4875
4870
4865
Elevation (ft amsl)
1990
1991
1992
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed


LWDS MW-1 HYDROGRAPH
4940
4935
4930
4925
4920
Elevation (ft amsl)
dry
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed


LWDS MW-2 HYDROGRAPH
4935
4930
4925
4920
Elevation (ft amsl)
dry
1993
1994
1995
1996
Date
Legend
USGS
SWHC2
SWHC3
Observed

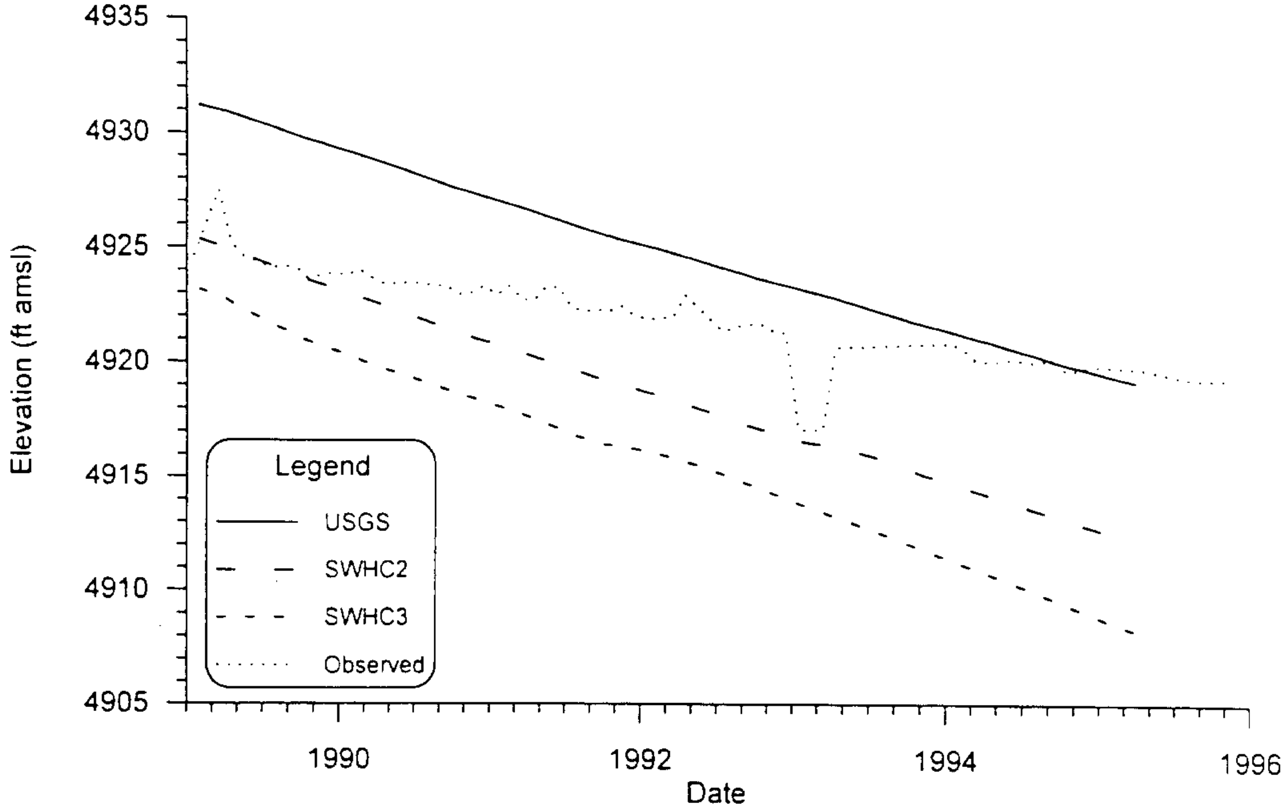


MVMWJ HYDROGRAPH
Elevation (ft amsl)
4920
4915
4910
4905
4900
4895
4890
4885
4880
4875
Legend
USGS
SWHC2
SWHC3
Observed
1989
1990
1991
1992
1993
1994
1995
1996
Date

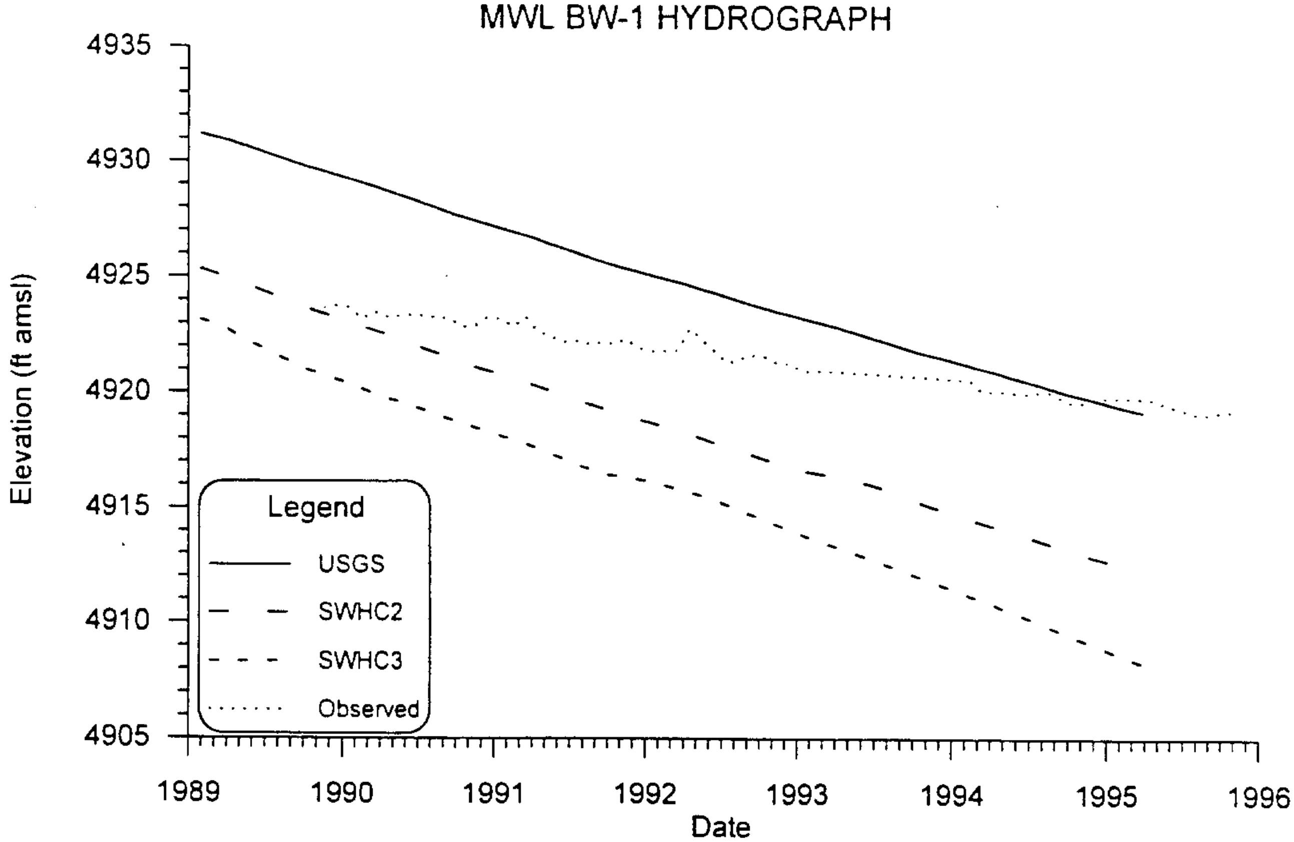


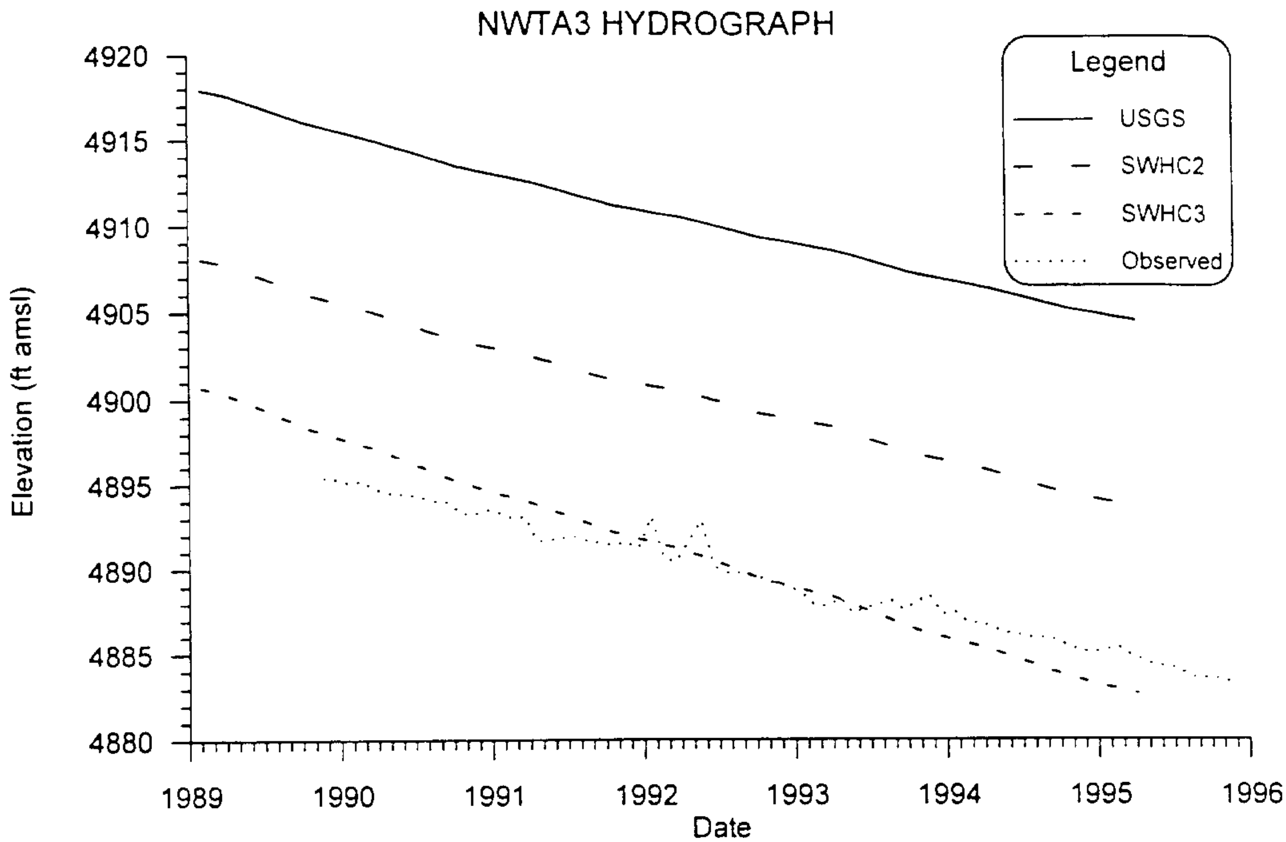
MVMWK HYDROGRAPH
Elevation (ft amsl)
4910
4905
4900
4895
4890
4885
4880
4875
4870
Legend
USGS
SWHC2
SWHC3
Observed
1989
1990
1991
1992
1993
1994
1995
1996
Date

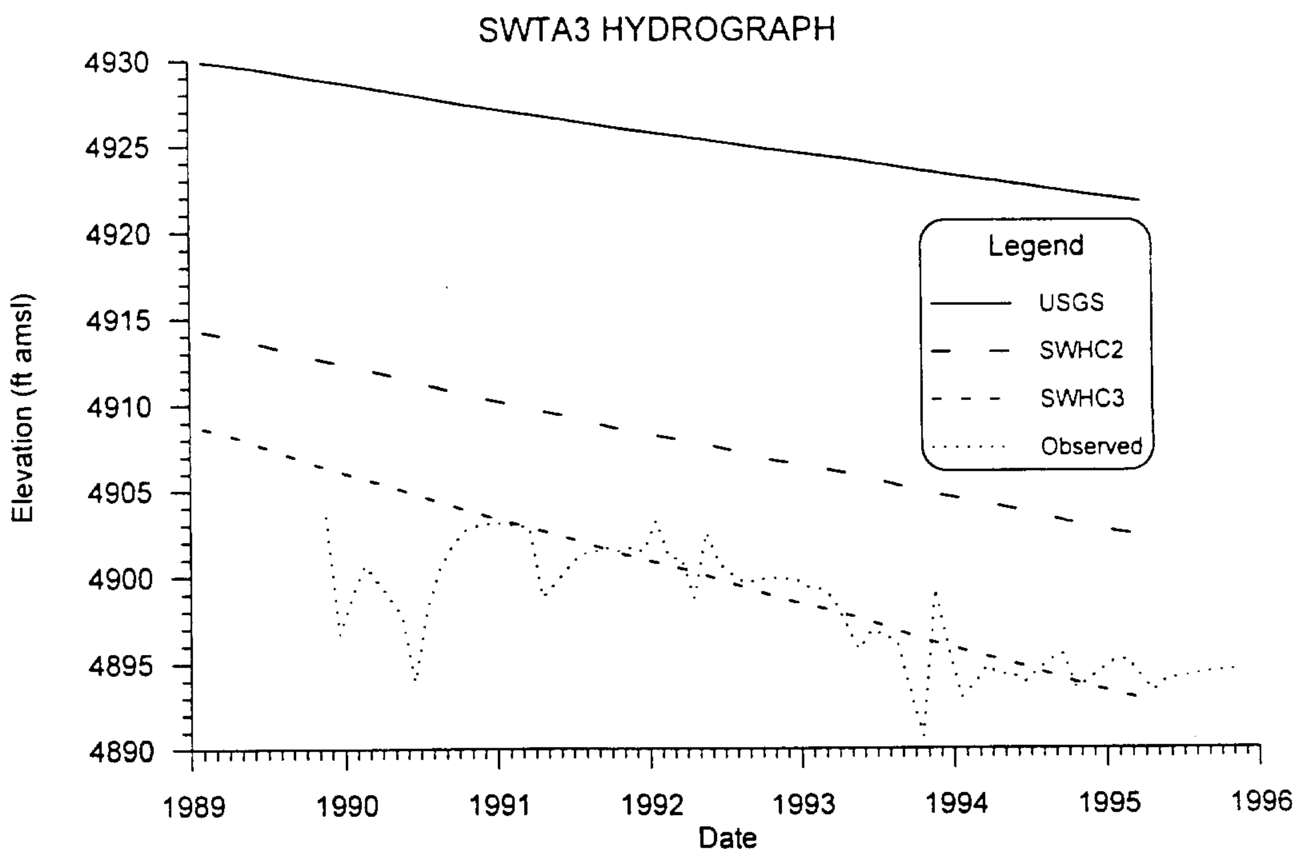
MWL MW-1 HYDROGRAPH

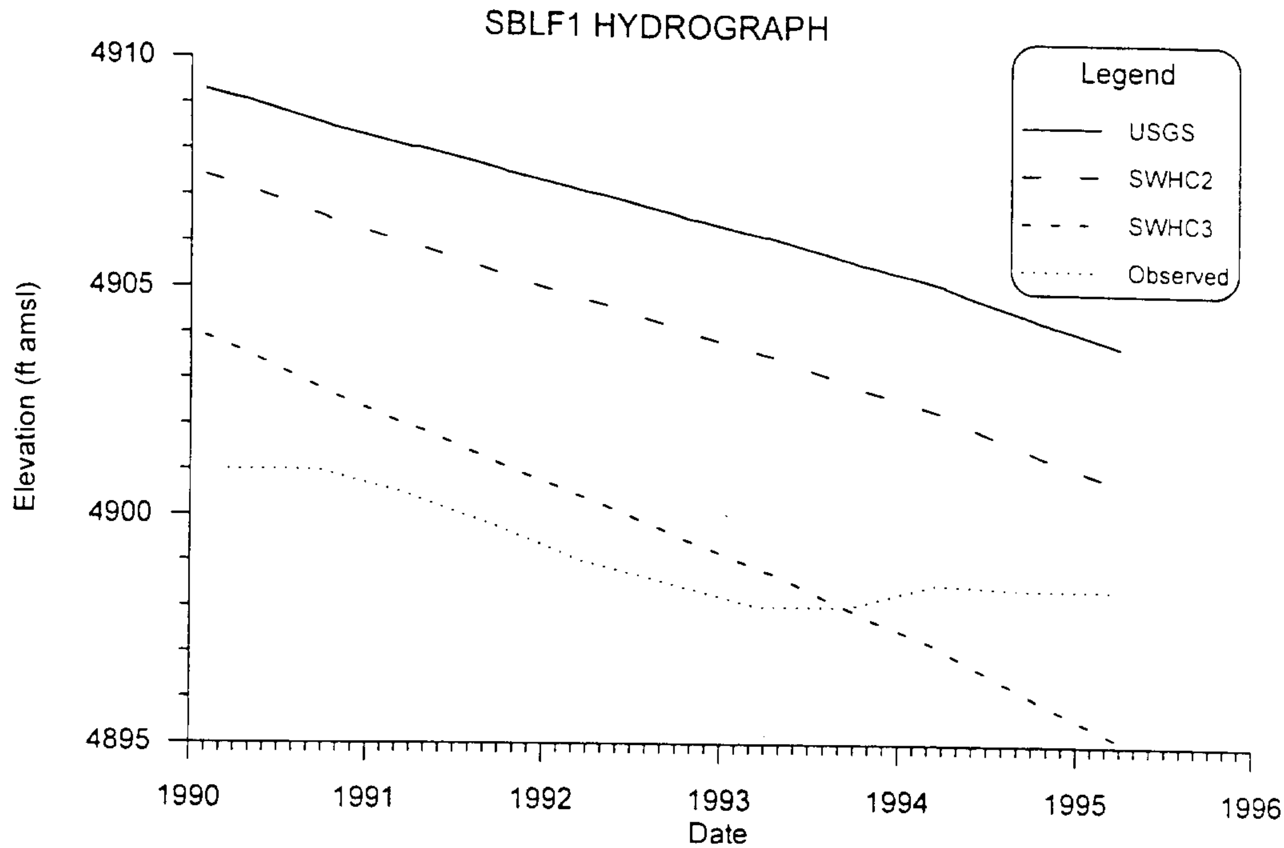


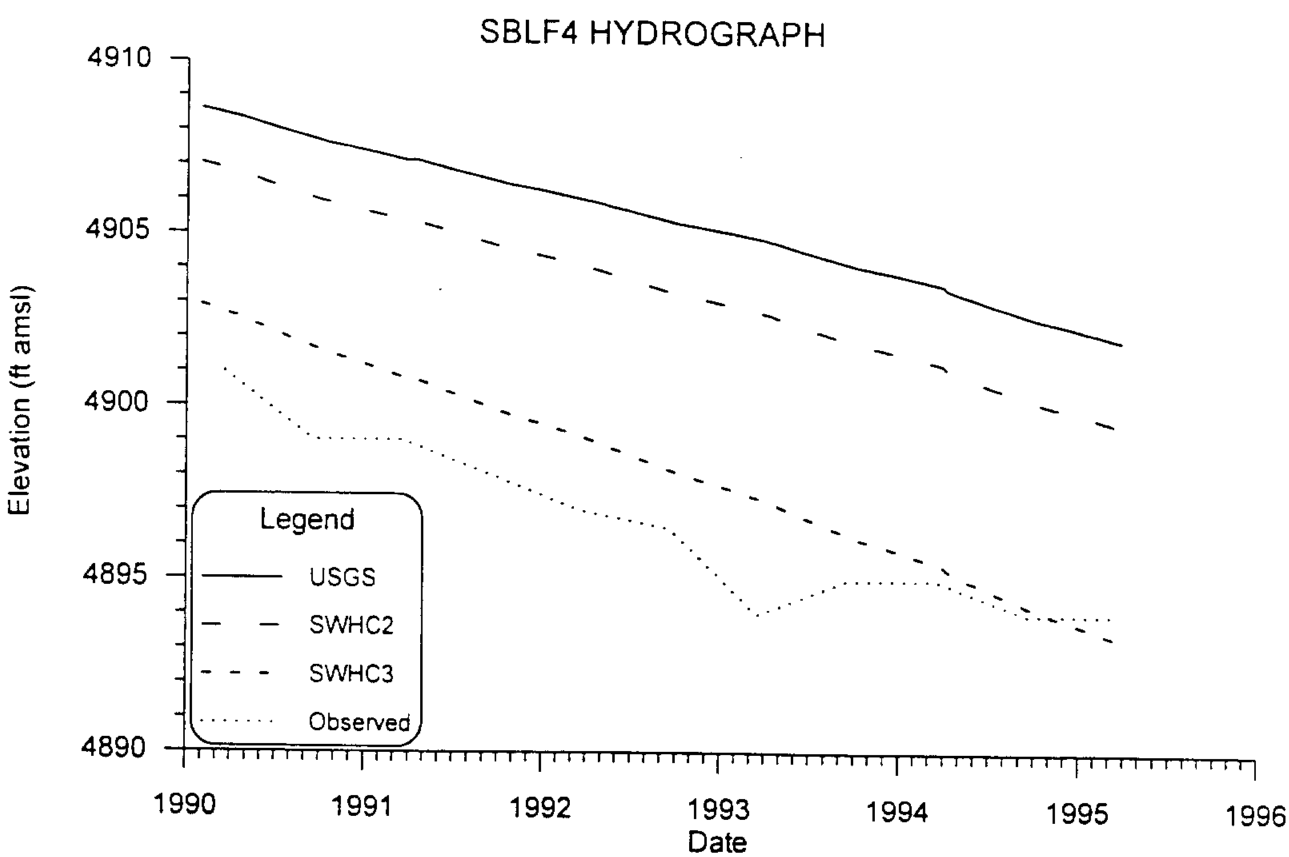
MWL BW-1 HYDROGRAPH

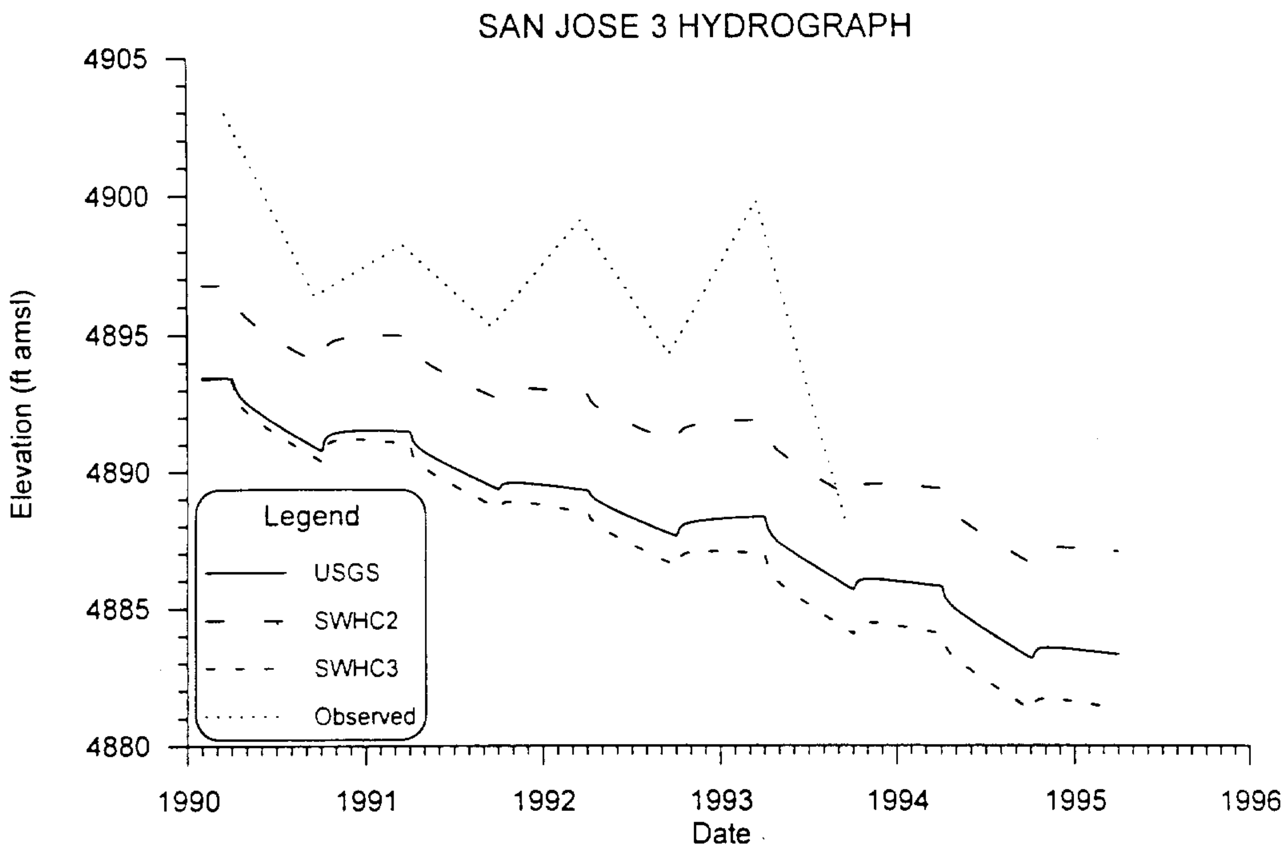


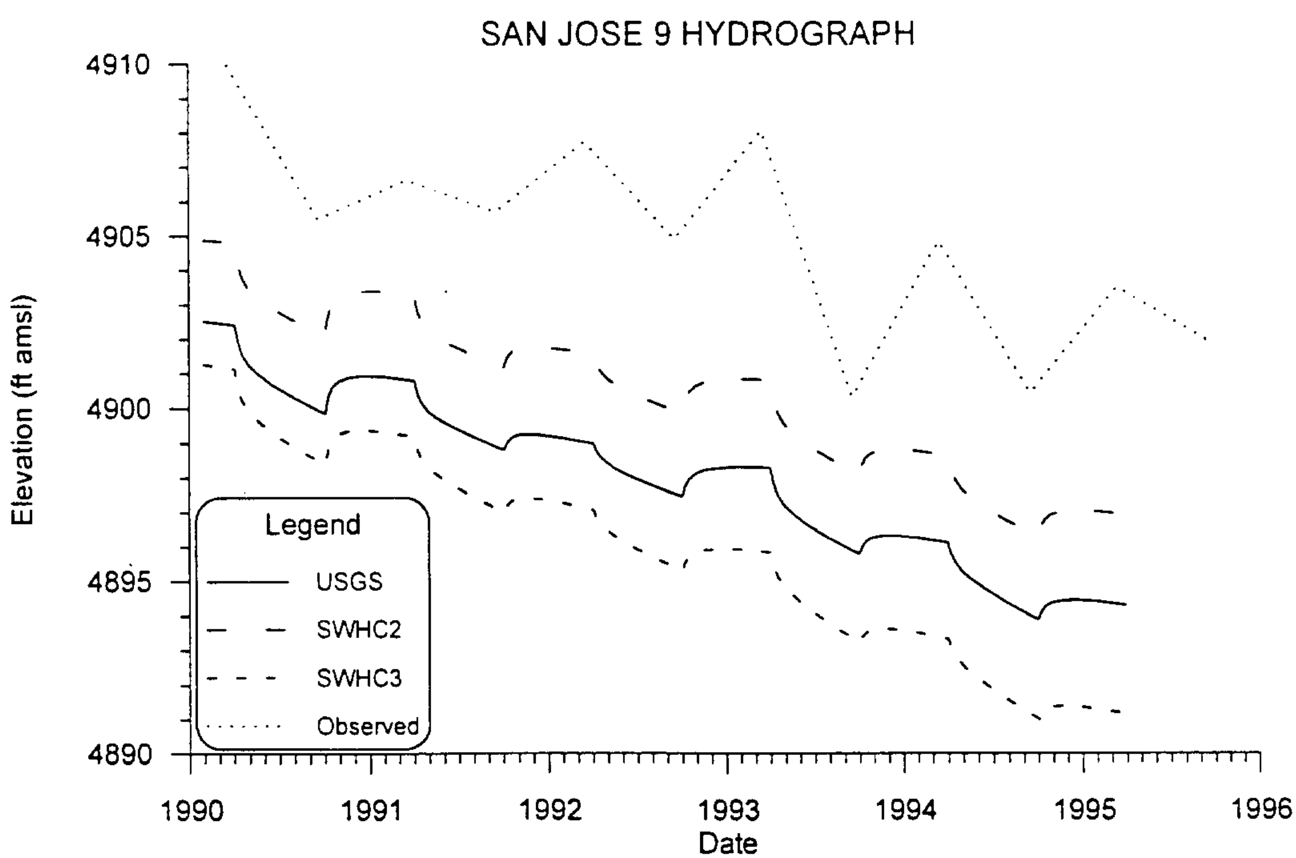

NWTA3 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4920
4915
4910
4905
4900
4895
4890
4885
4880
1989
1990
1991
1992
1993
1994
1995
1996
Date

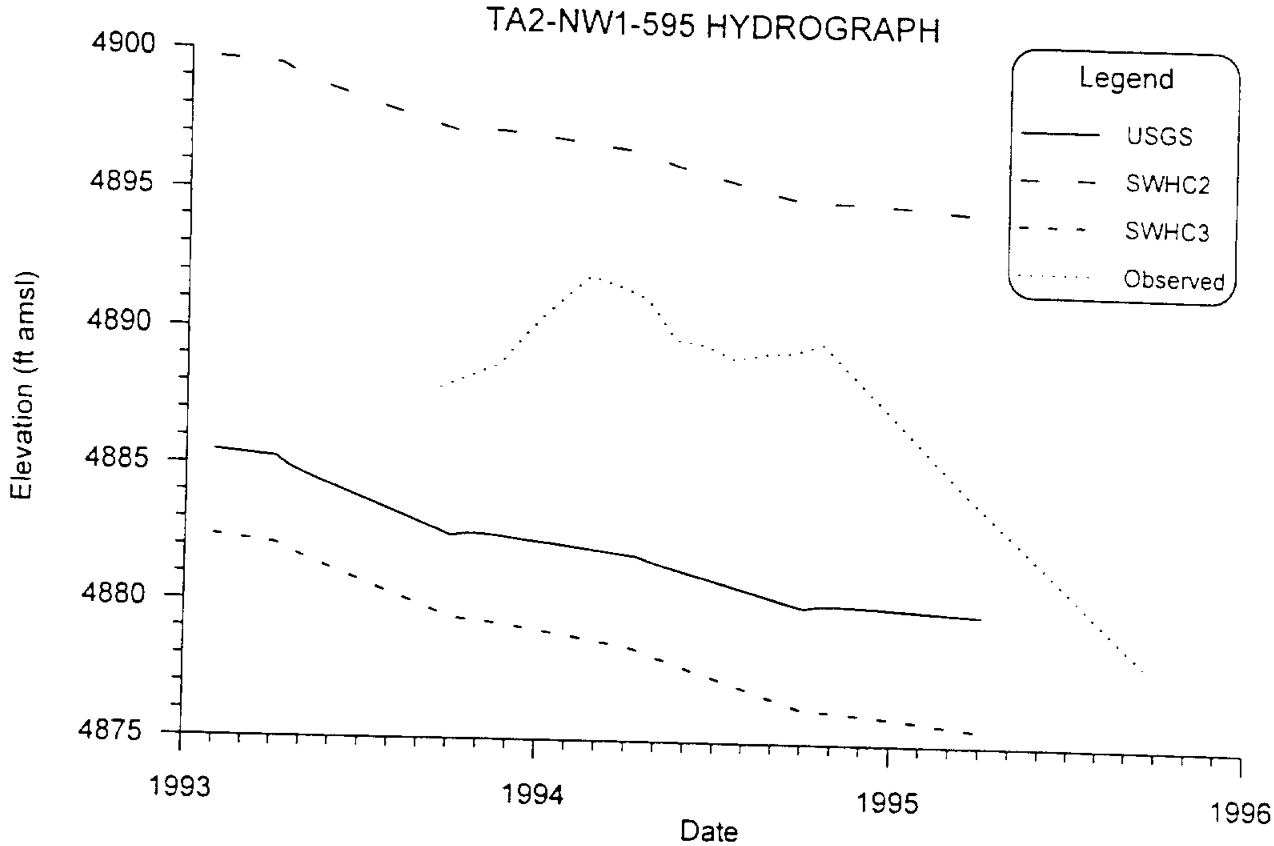

SWTA3 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4930
4925
4920
4915
4910
4905
4900
4895
4890
1989
1990
1991
1992
1993
1994
1995
1996
Date

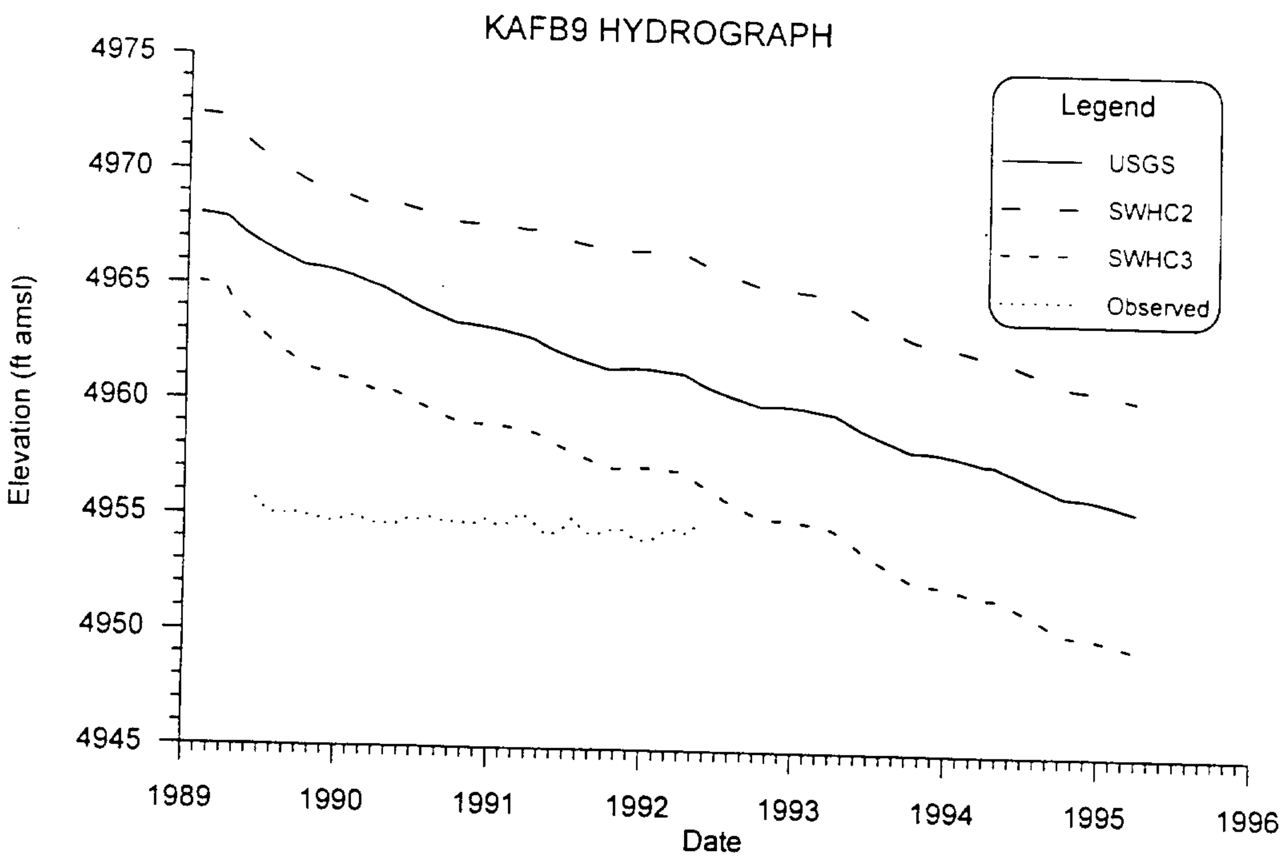

SBLF1 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4910
4905
4900
4895
1990
1991
1992
1993
1994
1995
1996
Date

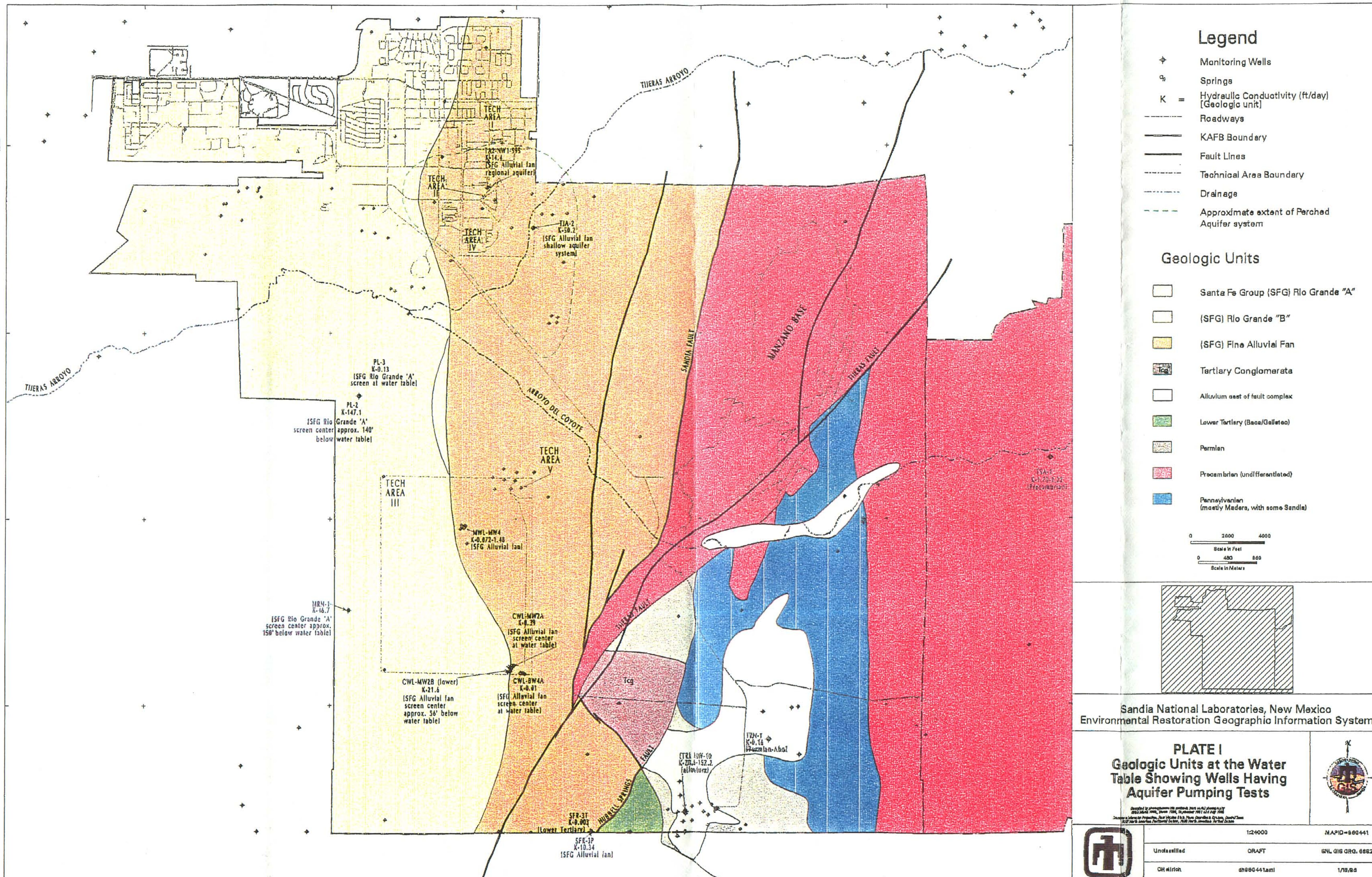

SBLF4 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4910
4905
4900
4895
4890
1990
1991
1992
1993
1994
1995
1996
Date


SAN JOSE 3 HYDROGRAPH
4905
4900
4895
4890
4885
4880
Elevation (ft amsl)
Legend
USGS
SWHC2
SWHC3
Observed
1990
1991
1992
1993
1994
1995
1996
Date

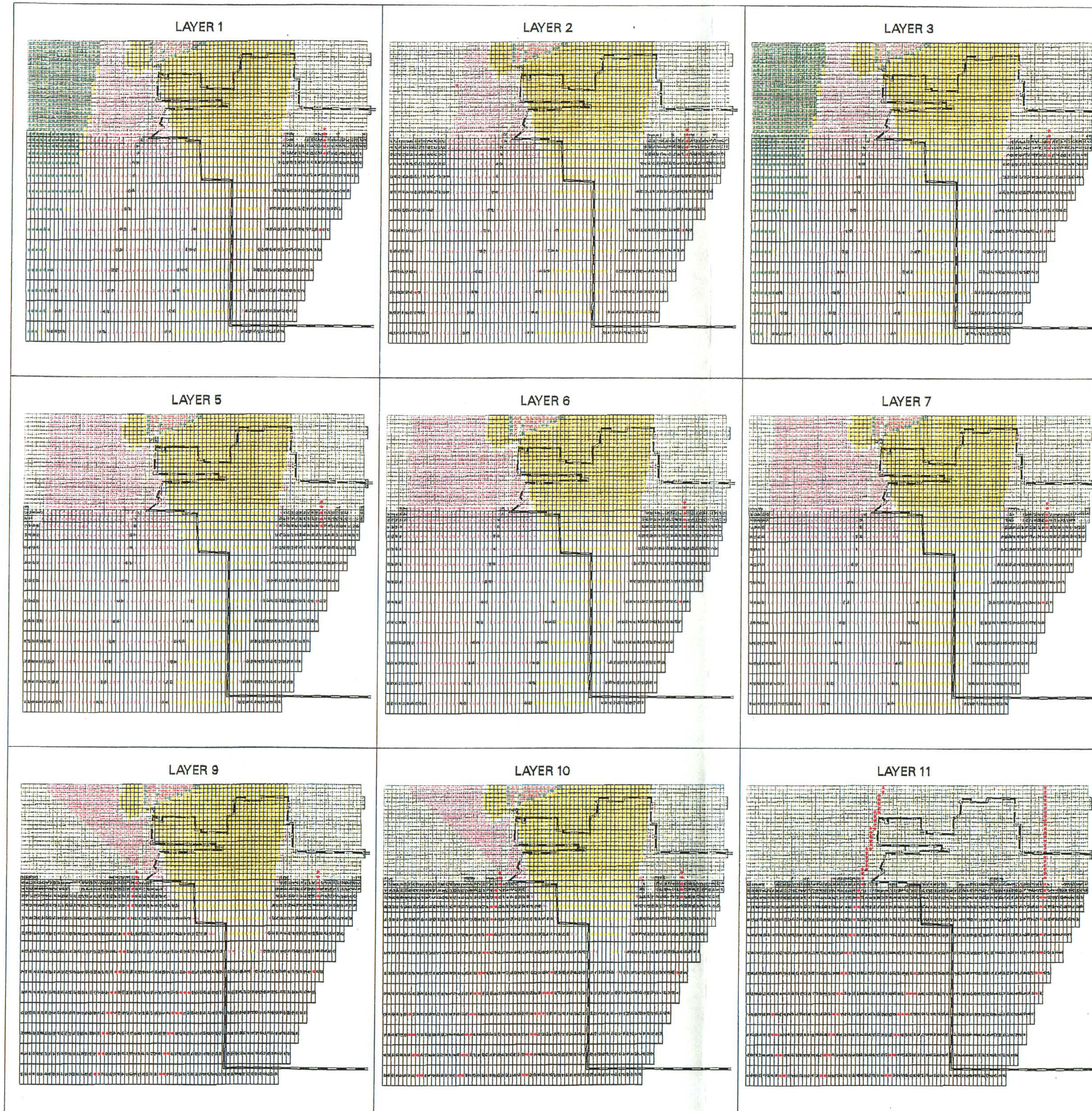

SAN JOSE 9 HYDROGRAPH
4910
4905
4900
4895
4890
Elevation (ft amsl)
Legend
USGS
SWHC2
SWHC3
Observed
1990
1991
1992
1993
1994
1995
1996
Date


TA2-NW1-595 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4900
4895
4890
4885
4880
4875
1993
1994
1995
1996
Date


KAFB9 HYDROGRAPH
Legend
USGS
SWHC2
SWHC3
Observed
Elevation (ft amsl)
4975
4970
4965
4960
4955
4950
4945
1989
1990
1991
1992
1993
1994
1995
1996
Date



Legend
Monitoring Wells
Springs
K = Hydraulic Conductivity (ft/day) [Geologic unit]
Roadways
KAFB Boundary
Fault Lines
Technical Area Boundary
Drainage
Approximate extent of Perched Aquifer system
Geologic Units
Santa Fe Group (SFG) Rio Grande "A"
(SFG) Rio Grande "B"
(SFG) Fine Alluvial Fan
Tertiary Conglomerata
Tcg
Alluvium east of fault complex
Lower Tertiary (Baca/Galisteo)
Permian
Precambrian (undifferentiated)
Pennsylvanian (mostly Madera, with some Sandia)
0 2000 4000
Scale in Feet
0 400 800
Scale in Meters
Sandia National Laboratories, New Mexico
Environmental Restoration Geographic Information System
PLATE I
Geologic Units at the Water Table Showing Wells Having Aquifer Pumping Tests
1:24000
NAPID=860441
Unclassified
DRAFT
SNL GIS ORG. 6682
OH ririon
dh960441aml
1/18/96
TIJERAS ARROYO
TECH AREA I
TECH AREA II
TECH AREA III
TECH AREA IV
TECH AREA V
TA2-NW1-595
K-14.4
(SFG Alluvial fan regional aquifer)
TJA-2
K-50.2
(SFG Alluvial fan shallow aquifer system)
PL-3
K-0.13
(SFG Rio Grande 'A' screen at water table)
PL-2
K-147.1
(SFG Rio Grande 'A' screen center approx. 140' below water table)
ARROYO DEL COYOTE
SANDIA FAULT
MANZANO BASE
TIJERAS FAULT
MWL-MW4
K-0.072-1.48
(SFG Alluvial fan)
MRN-1
K-46.7
(SFG Rio Grande 'A' screen center approx. 150' below water table)
CWL-MW2A
K-8.39
(SFG Alluvial fan screen center at water table)
CWL-MW2B (lower)
K-21.6
(SFG Alluvial fan screen center approx. 56' below water table)
CWL-BW4A
K-8.41
(SFG Alluvial fan screen center at water table)
Tcg
TRN-1
K-0.16
(Permian-Abo)
CTF-MW-10
K-20.3-152.2
(alluvium)
HUBBELL SPRINGS
FAULT
SFR-3T
K-8.80T
(Lower Tertiary)
SFR-3P
K-10.34
(SFG Alluvial fan)

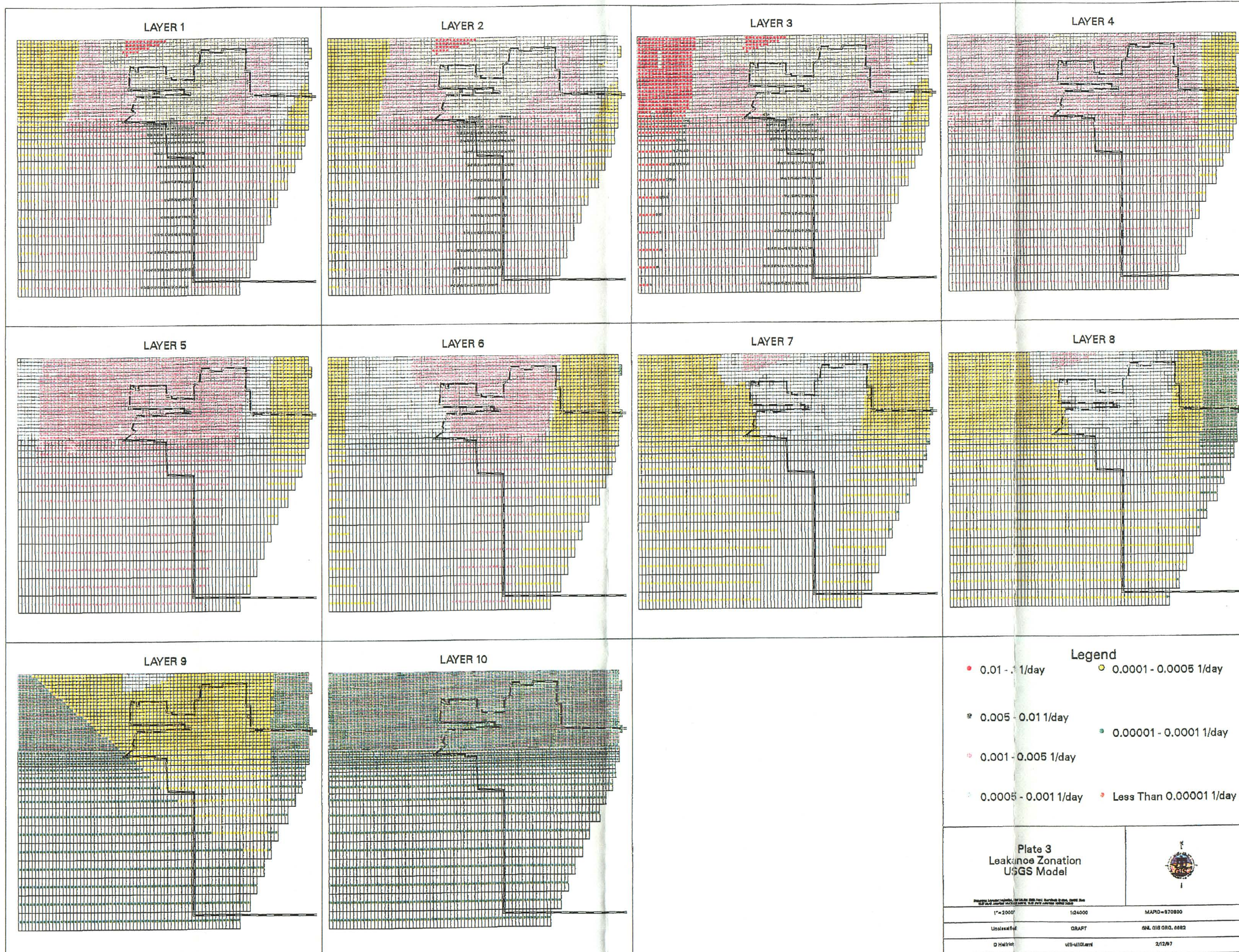


Legend

- 0.01 - 0.9 ft/day
- 1 - 10.9 ft/day
- 11 - 19.9 ft/day
- 20 - 29.9 ft/day
- 30 - 39.9 ft/day
- 40 - 49.9 ft/day
- 50 - 99.9 ft/day
- 100-300 ft/day

Plate 2
Horizontal Hydraulic Conductivity Zonation
USGS Model

1"=2000'	1:24000	MAPID=870798
Unclassified	DRAFT	SNL GIS ORG. 6682
D Helfrich	u11k-u11k.aml	10/30/97



LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
LAYER 6
LAYER 7
LAYER 8
LAYER 9
LAYER 10
Legend
0.01 - .1 1/day
0.0001 - 0.0005 1/day
0.005 - 0.01 1/day
0.00001 - 0.0001 1/day
0.001 - 0.005 1/day
0.0005 - 0.001 1/day
Less Than 0.00001 1/day
Plate 3
Leakance Zonation
USGS Model
1"=2000'
1:24000
MAPID=970800
Unclassified
DRAFT
SNL GIS ORG. 6682
D Helfrich
2/12/97

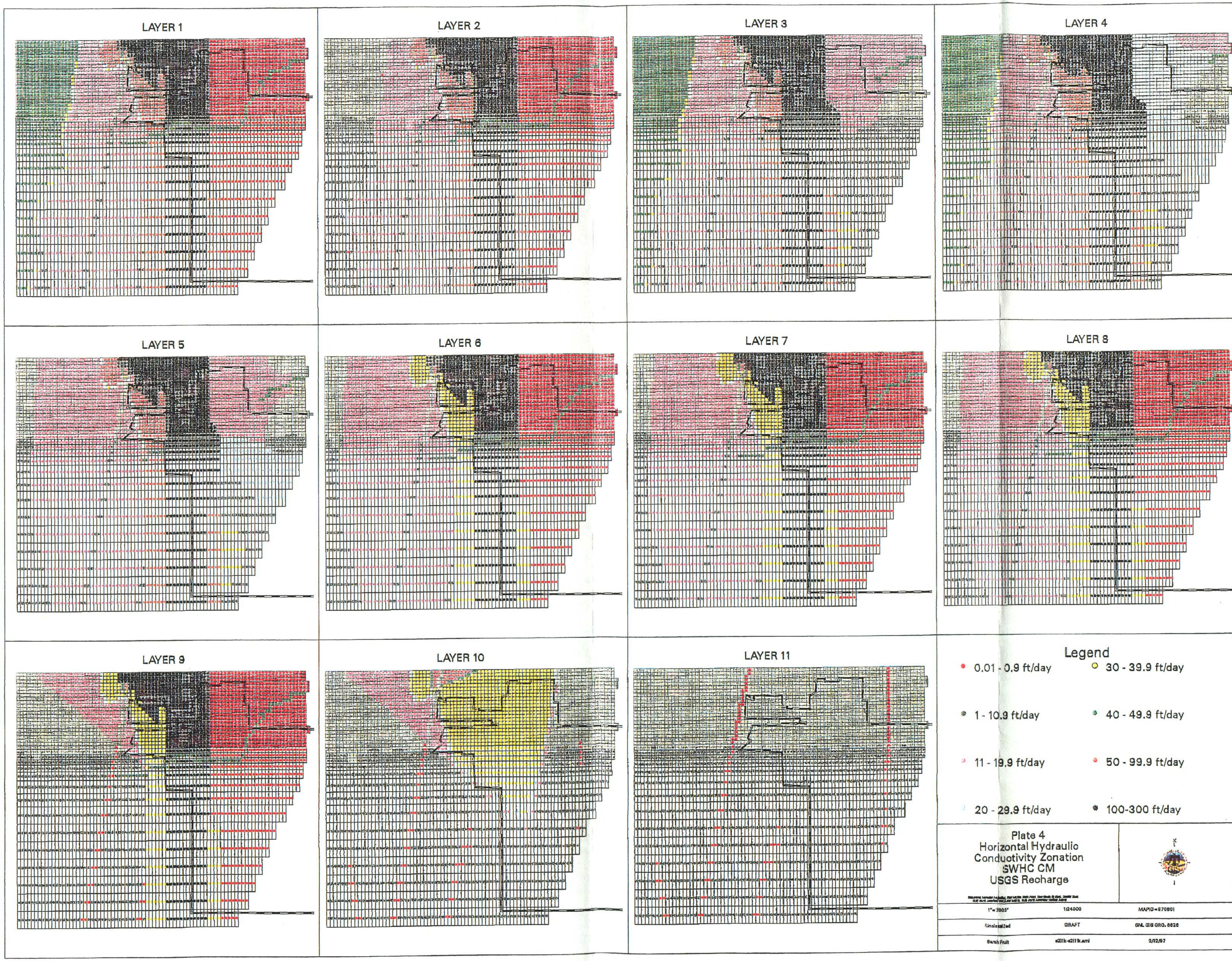
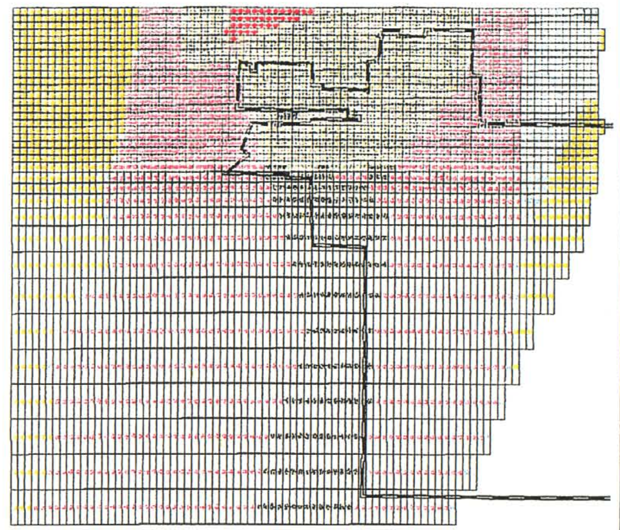


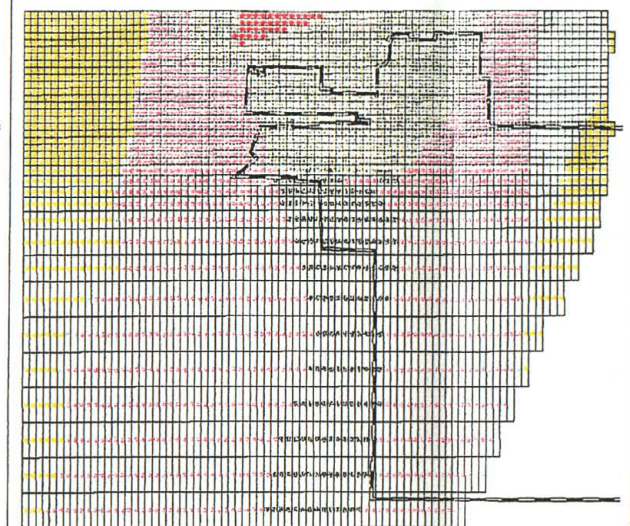
Plate 4
Horizontal Hydraulic
Conductivity Zonation
SWHC CM
USGS Recharge

1"=2000'	1:24000	MAPID=970801
Unclassified	DRAFT	SNL GIS ORG. 6626
Sarah Fruit	s2l1k-s2l11k.aml	2/12/97

LAYER 1

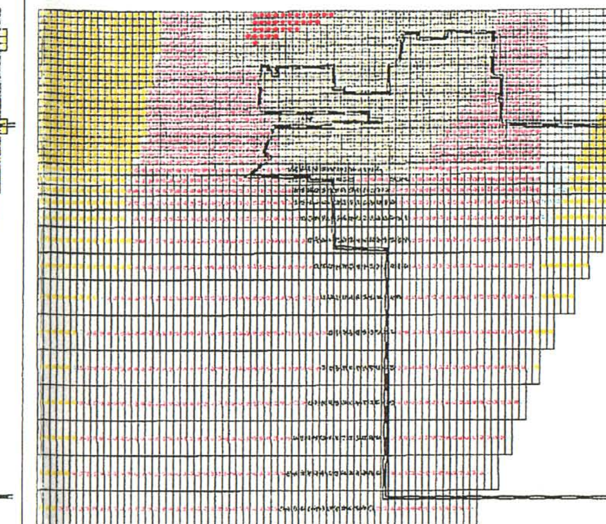


LAYER 2

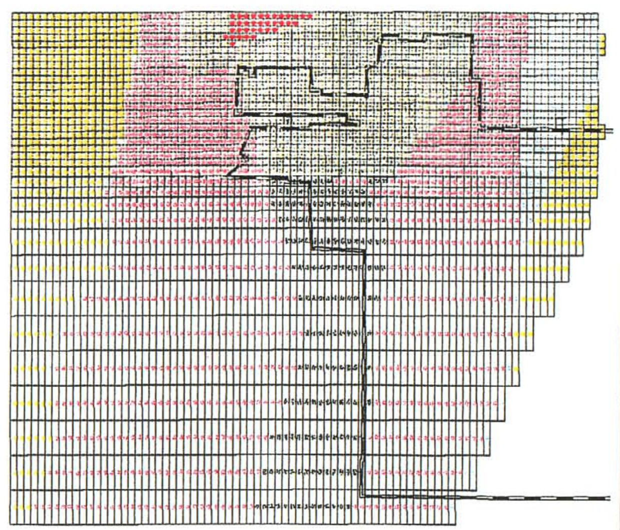


LAYER 3

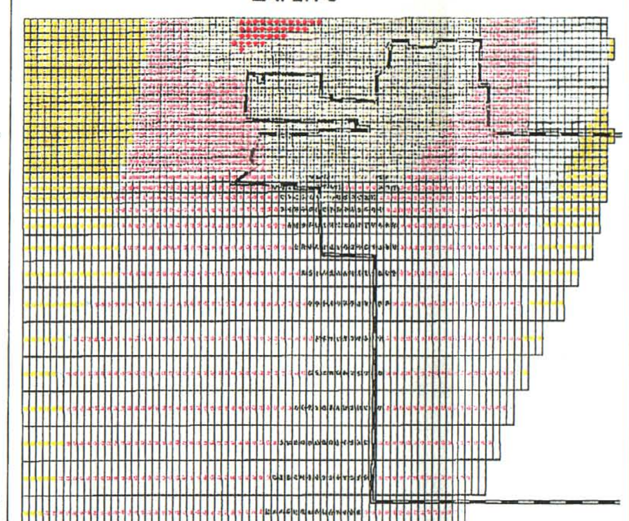
LAYER 4



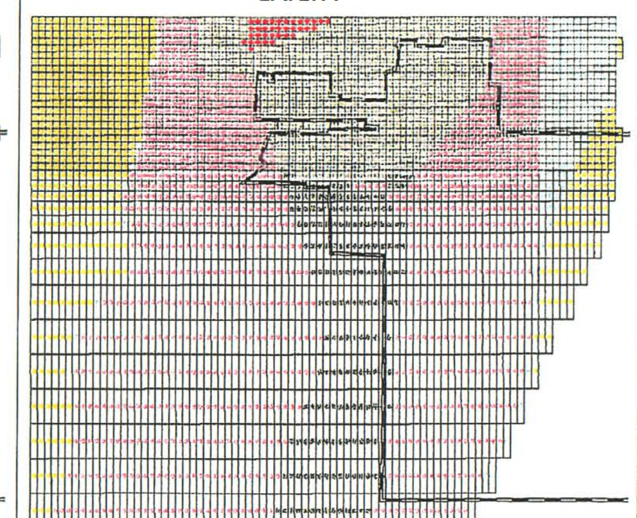
LAYER 5



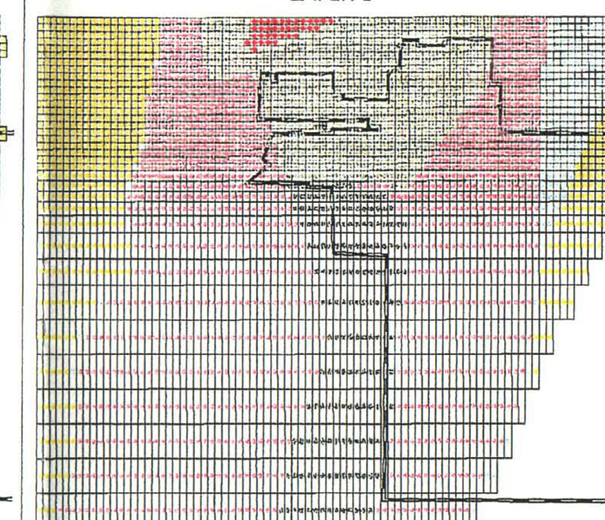
LAYER 6



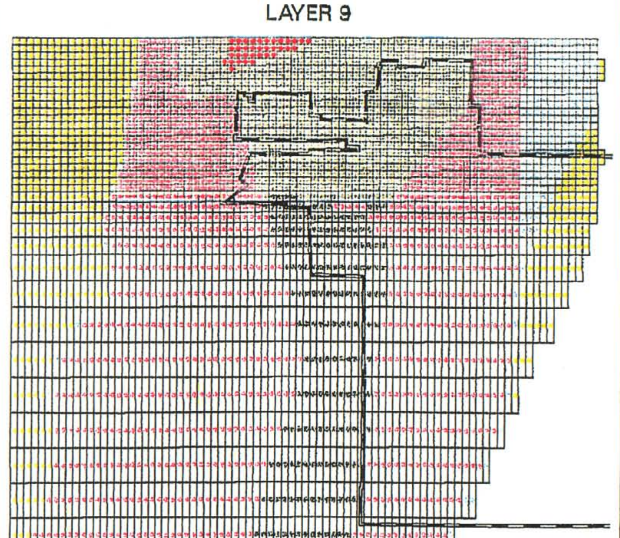
LAYER 7



LAYER 8



LAYER 9



LAYER 10

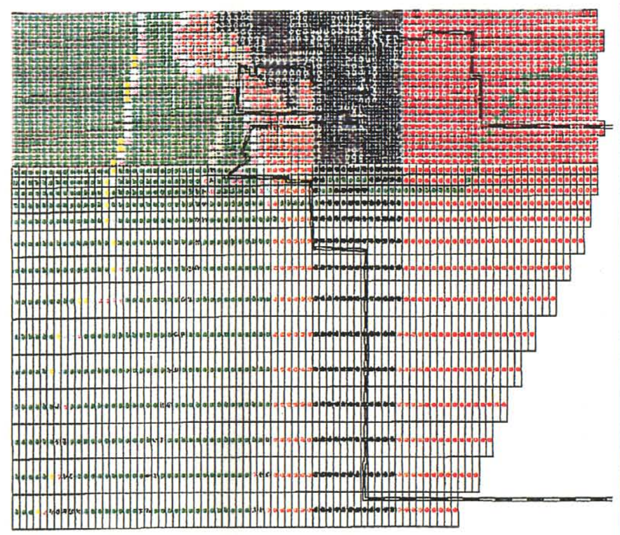
Legend

- 0.01 - .1 1/day
- 0.0001 - 0.0005 1/day
- 0.005 - 0.01 1/day
- 0.00001 - 0.0001 1/day
- 0.001 - 0.005 1/day
- 0.0005 - 0.001 1/day
- Less Than 0.00001 1/day

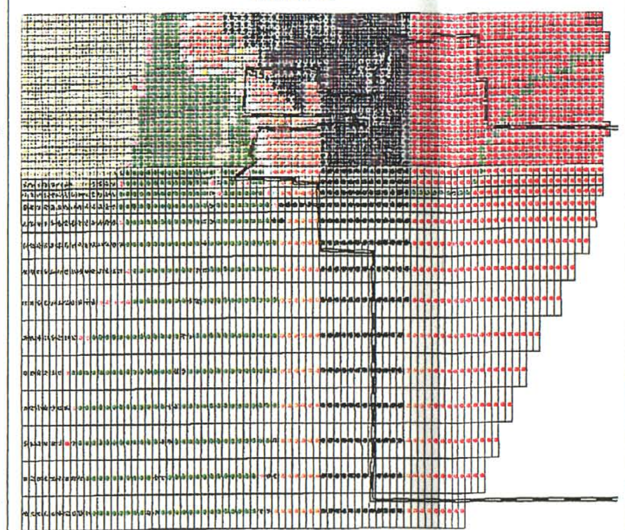
Plate 5
Leakance Zonation
SWHC CM
USGS Recharge

1"=2000'	1:24000	MAPID=970802
Unclassified	DRAFT	SNL GIS ORG. 6682
D Helrich	s2l1l-s2l10l.aml	2/13/97

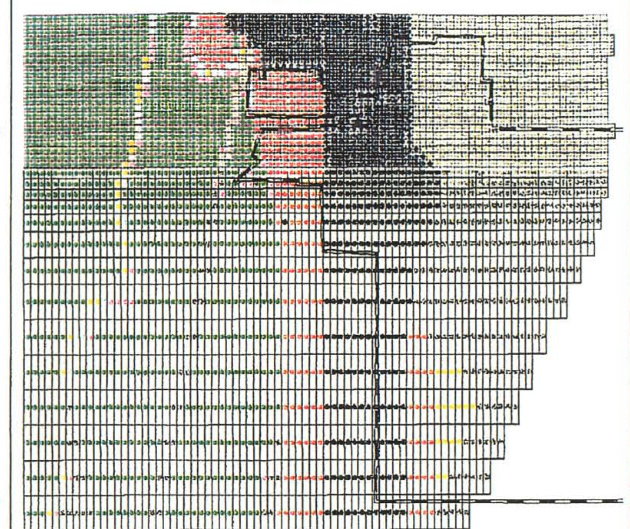
LAYER 1



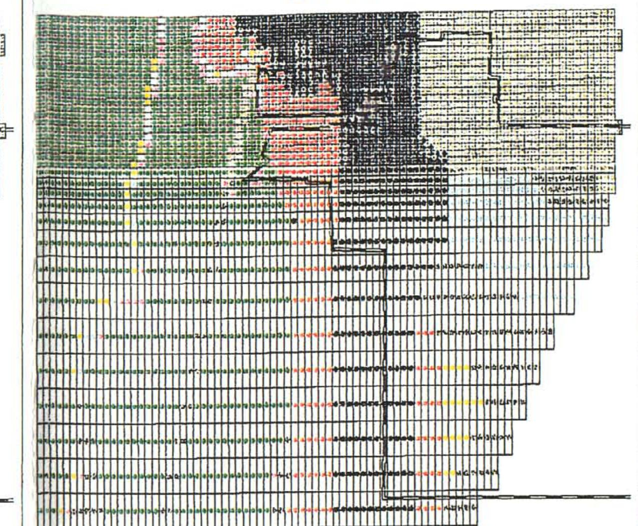
LAYER 2



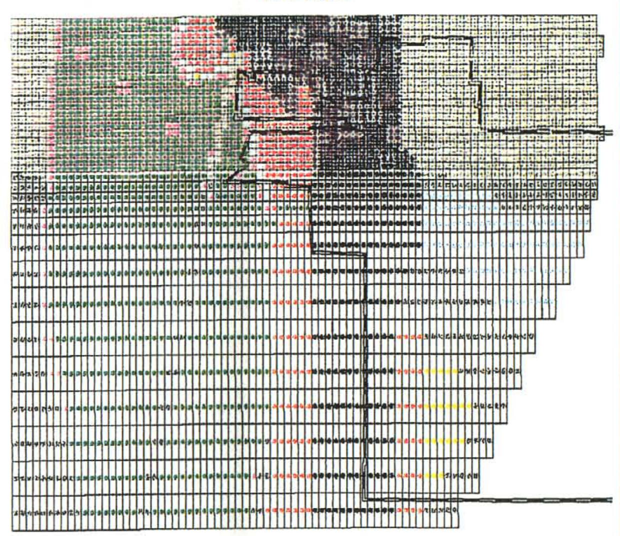
LAYER 3



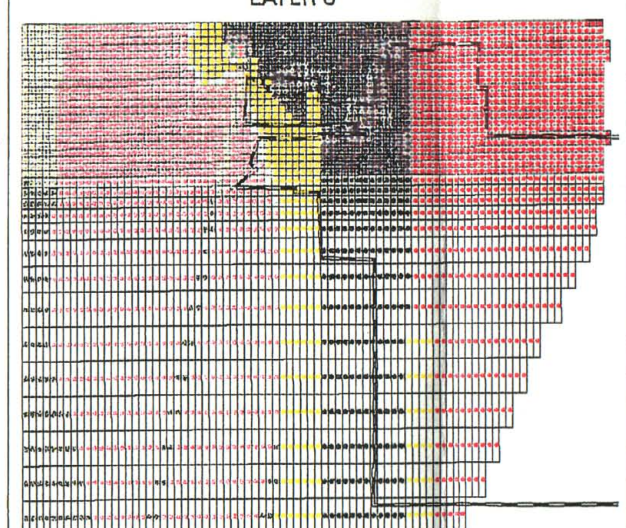
LAYER 4



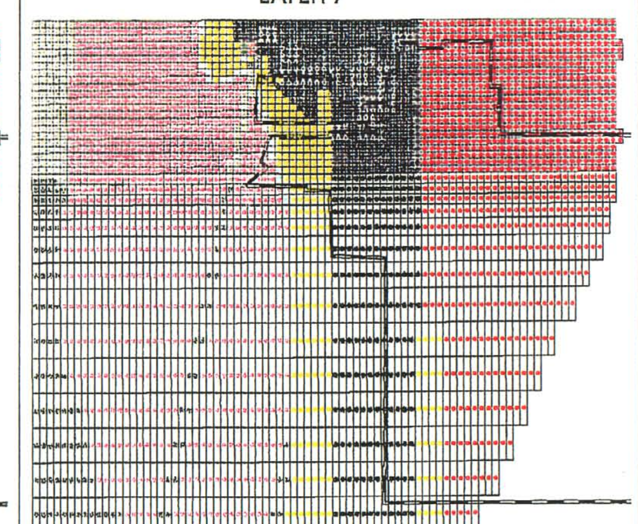
LAYER 5



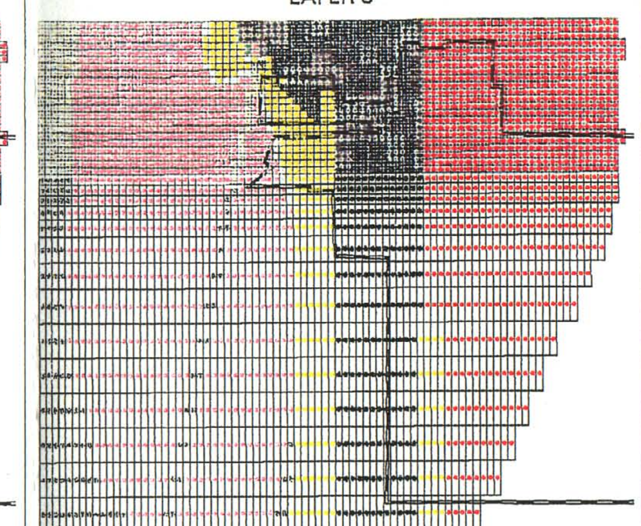
LAYER 6



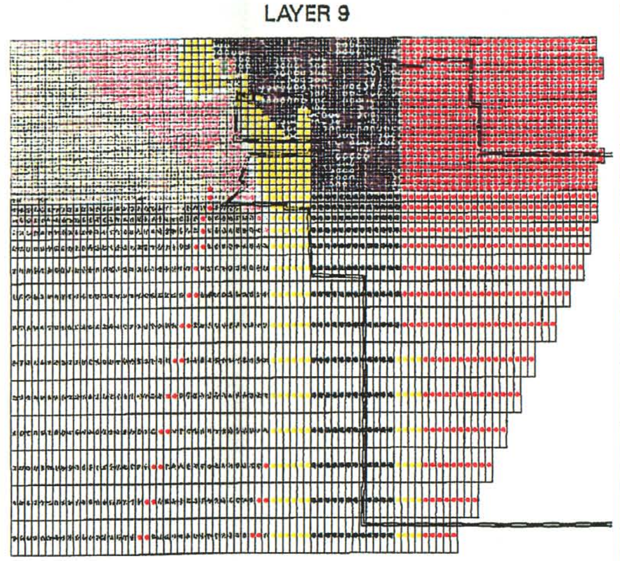
LAYER 7



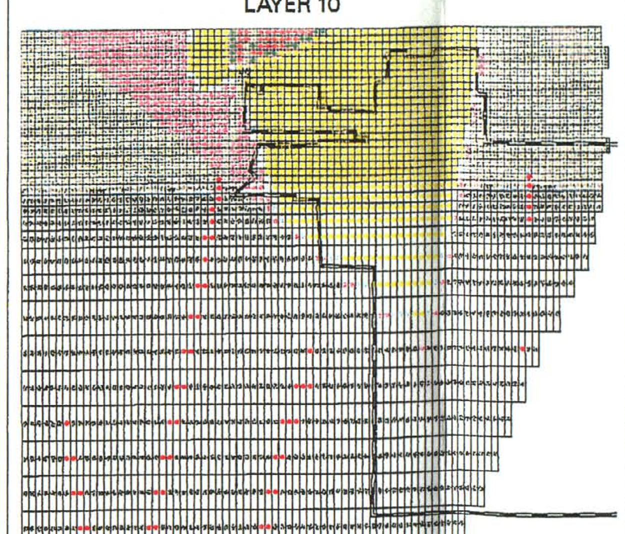
LAYER 8



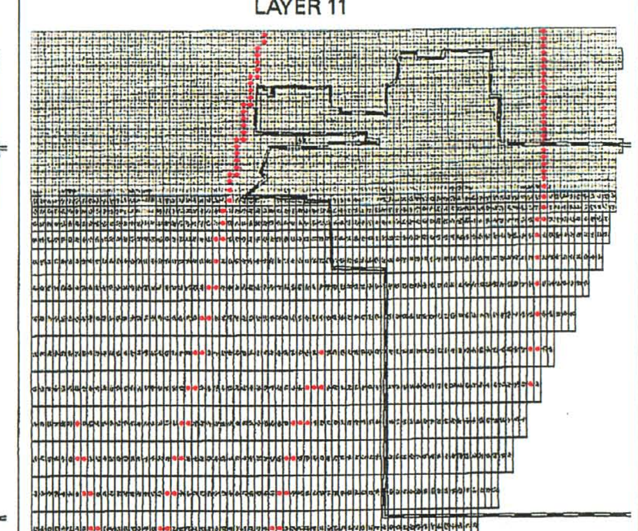
LAYER 9



LAYER 10



LAYER 11



Legend

- 0.01 - 0.9 ft/day
- 30 - 39.9 ft/day
- 1 - 10.9 ft/day
- 40 - 49.9 ft/day
- 11 - 19.9 ft/day
- 50 - 99.9 ft/day
- 20 - 29.9 ft/day
- 100-300 ft/day

Plate 6
Horizontal Hydraulic
Conductivity Zonation
SWHC CM
SWHC Recharge

1"=2000'	1:24000	MAPID=870803
Unclassified	DRAFT	SNL GIS ORG. 6682
D Helfrich	s3l1k-s3l1k.aml	2/14/97

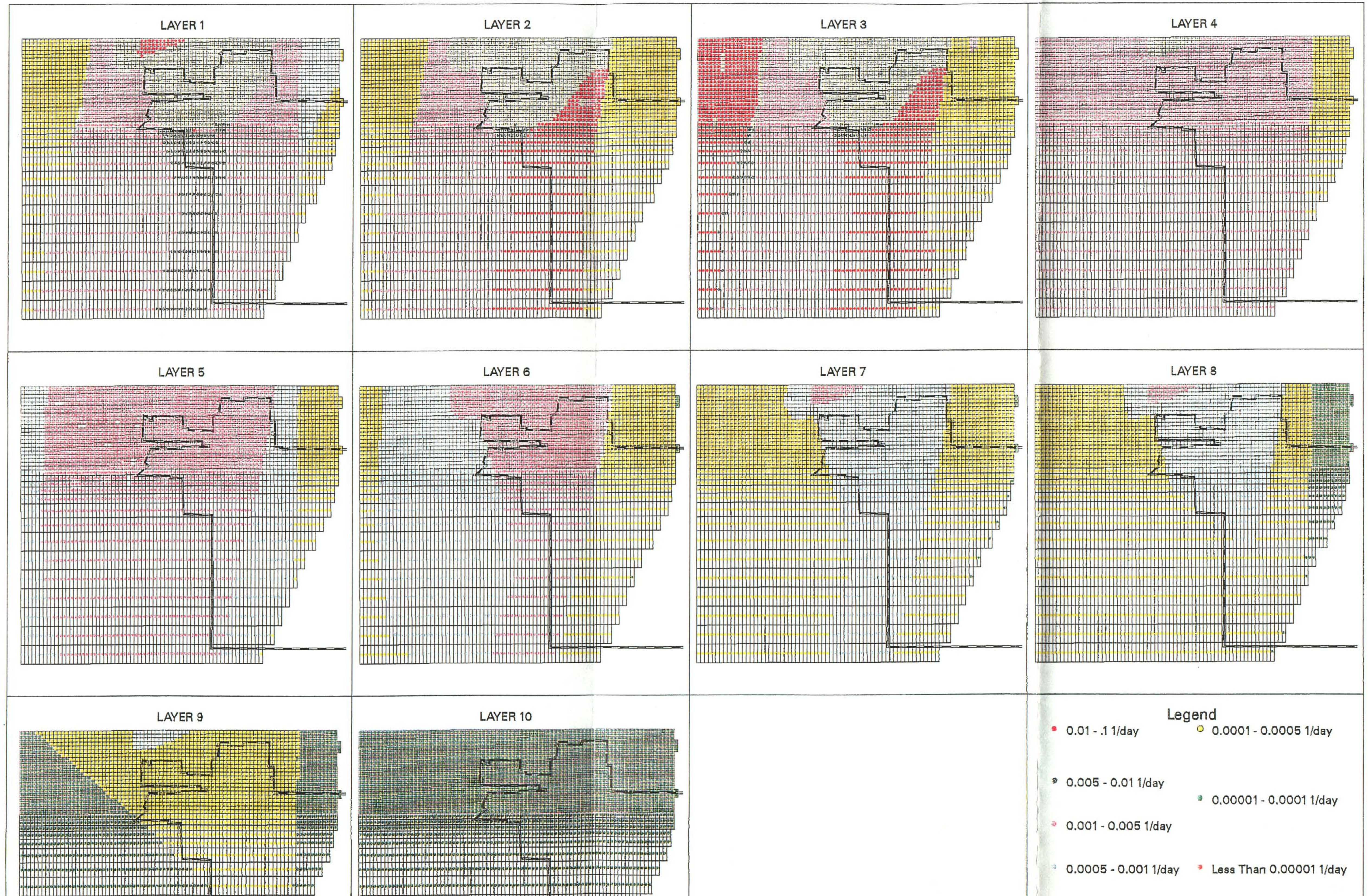


Plate 7
Leakance Zonation
SWHC CM
SWHC Recharge

1"=2000'	1:24000	MAPID=970804
Unclassified	DRAFT	SNL GIS ORG. 6682
D'Helfrich	s3111-s3110l.aml	2/14/97

BASIC ELEMENTS OF THE SNL/NM SITE-WIDE HYDROGEOLOGIC CONCEPTUAL MODEL

Major Model Element - Geology

Sub-element	REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)		
Stratigraphy	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	The sequence (units, age, major unconformities) • Geology Report, Section 1.4.2 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.1.2 (SNL/NM,1996a)	**Geologic Column** • Geology Report, Fig 1.4-4 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Fig 3.1.2-1 (SNL/NM,1996a)	Information/illustrations also presented in SWHC 1994 Annual Report, Section 3.1.1 (SNL/NM,1995b) and Annual Groundwater Monitoring Reports, such as the Groundwater Protection Program Calendar Year 1996 Annual Groundwater Monitoring Report, Section 2.1 (SNL/NM, 1997).
	Each individual unit (lithology, thickness, extent, variability, nature of contact with unit below) • Geology Report, Section 1.4.2 and Appendix C (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.1.2 (SNL/NM,1996a)	**Measured Section(s)** • Geology Report, Fig 3.1-6; Appendix E, pgs E-38 and E-39 (SNL/NM, 1995a)	
		Well Logs • Geology Report, Figs 3.1-3 and 3.1-5; Appendix A (all), (SNL/NM, 1995a)	Complete SNL/NM well files, including logs, are maintained in two places. Hard copy files are maintained at the ES&H Records Center. Electronics records are maintained in the Environmental Restoration Data Management System (ERDMS) which runs on Oracle on a Sun platform.
		Surficial Geologic Cross Section(s) • Geology Report, Figs 2.1-5a-b, 2.1-10a-g, 2.1-14a-c, 2.1-18, 2.1-20a-c, and 2.1-25 (SNL/NM, 1995a)	

Major Model Element - Geology			
Sub-Element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Stratigraphy	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
		Subsurface Geologic Cross Section(s) • Geology Report, Figs 3.1-4, 3.1-14 through 3.1-21, and 3.2-1 through 3.2-3 (SNL/NM, 1995a)	
		Fence Diagram(s) • None.	Detailed stratigraphic correlation is not meaningful at the site-wide scale. Site-specific fence diagram could be developed for local areas with many wells such as ITRI, CWL, MWL, etc.
		Depth Map(s) - to top of unit(s) • Geology Report, Plates XV (bedrock elevation of subsurface bedrock) and XVI (bedrock elevation of subsurface bedrock - Arroyo del Coyote (SNL/NM, 1995a)	
		Thickness Map(s) - of interval(s) of interest • Geology Report, Plates XI (elevation structure map on regional water table and geologic units at the regional water table (SNL/NM, 1995a)	
		Attribute Map(s) - grain size, percent sand, number of sand layers, sand/shale ratio, etc. • Geology Report, Fig 4.1-1 (soil infiltration capacity map) and Tables 2.0-1 (grain size and clast composition) and B.3-1 (listing of grain size sampling projects) (SNL/NM, 1995a)	A surface soil map is available from the USDA Soil Conservation Survey (Hacker, 1977).

Major Model Element - Geology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Structure	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Regional Features - domes, uplifts, rifts, basins • Geology Report, Section 1.4 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.1.1 (SNL/NM, 1996a)	**Geologic Maps** • Geology Report, Figs 2.1-1, 2.1-4, 2.1-8, 2.1-13, 2.1-15, 2.1-17, 2.1-19, 2.1-24, and 3.0-1; also Plates I through X and XII through XIV (SNL/NM, 1995a)	Information/illustrations also presented in Annual Groundwater Monitoring Reports, such as the Groundwater Protection Program Calendar Year 1996 Annual Groundwater Monitoring Report, Section 2.1 (SNL/NM, 1997).
	Local dip/strike • Geology Report, Section 3.1.2 and Appendix E (SNL/NM, 1995a)	**Surficial Geologic Cross Section(s)** • Geology Report, Figs 2.1-5a-b, 2.1-10a-g, 2.1-14a-c, 2.1-18, 2.1-20a-c, and 2.1-25 (SNL/NM, 1995a)	
	Folding • Geology Report, Section 3.1.2 (SNL/NM, 1995a)	**Subsurface Geologic Cross Section(s)** • Geology Report, Figs 3.1-4, 3.1-14 through 3.1-21, and 3.2-1 through 3.2-3 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Fig 3.1.1-2 (SNL/NM, 1996a)	
	Faulting • Geology Report, Sections 1.3, 1.4, 2.1.2, 3.1.2, and Appendix E (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.1.1 (SNL/NM, 1996a)	**Fence Diagram(s)** • None.	Detailed stratigraphic correlation is not meaningful at the site-wide scale. Site-specific fence diagram could be developed for local areas with many wells such as ITRI, CWL, MWL, etc.
	Fracture/joint systems • Geology Report, Section 2.2.4 and Appendix E (SNL/NM, 1995a)	**Structure Map(s) - elevation of top of unit(s)** • Geology Report, Plates XI (elevation structure map on regional water table and geologic units at the regional water table), XV (bedrock elevation of subsurface bedrock), and XVI (bedrock elevation of subsurface bedrock - Arroyo del Coyote) (SNL/NM, 1995a)	

Major Model Element - Geology			
Sub-Element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Geomorphology	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Relief • Geology Report, Section 1.4 and Appendix E (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.1.1 (SNL/NM, 1996a)	**Topographic Map** • Geology Report, Fig 1.4-6 and 4.0-1 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Fig 3.1.3-2, 3.2.4-3, and 3.2.4-4 (SNL/NM, 1996a)	
	Major Landforms • Geology Report, Section 1.4 and Appendix E (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.1.1 (SNL/NM, 1996a)	**Topographic Profile** • Geology Report, Figs 3.1-14 through 3.1-20 and 3.2-1 through 3.2-3 (SNL/NM, 1995a)	Information/illustrations also presented in Groundwater Protection Program Calendar Year 1996 Annual Groundwater Monitoring Report, Section 2.1 (SNL/NM, 1997).
	Soil Types • Geology Report, Sections 1.4.4.2, Sections 2 and 3, and Appendix D (SNL/NM, 1995a) • SWHC 1995 Annual Report, Sections 3.1.2.6 and 3.1.4 (SNL/NM, 1996a)	**Soil Map** • Geology Report, Figs 1.4-7, 2.1-6, 2.1-9, 2.1-11, 2.1-21, and 2.1-22; Tables 3.1-2, 3.1-3, and 3.1-4; and Appendix D (SNL/NM, 1995a) • SWHC 1995 Annual Report, Fig 3.1.4-1 (SNL/NM, 1996a)	A surface soil map is available from the USDA Soil Conservation Survey (Hacker, 1977). A summary description based on Hacker (1977) is contained in the SWHC 1993 Annual Report, Section 4.1.3.2 (SNL/NM, 1994).
		Aerial Photograph(s) • Geology Report, Fig 1.4-3, 2.1-3, and 2.2-3 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Fig 3.1.1-3 (SNL/NM, 1996a)	
		Ground-level photograph(s) • Geology Report, Appendix E (SNL/NM, 1995a)	Few ground level photos have been published in SWHC reports. However, these types of photos exist in project files.

BASIC ELEMENTS OF THE SNL/NM SITE-WIDE HYDROGEOLOGIC CONCEPTUAL MODEL			
Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Surface Water	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Major Features (rivers, lakes, etc) • Geology Report, Sections 1.4 and 2.1.1.3 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Sections 3.1.1, 3.2.1, and 3.2.2 (SNL/NM, 1996a)	**Hydrographs** • None	A summary description of the general area setting is described in the SWHC 1993 Annual Report, Section 1.3 (SNL/NM, 1994). Hydrographs are presented in SWHC 1994 Annual Report, Appendix C, Fig C-5 (SNL/NM, 1995b). No hydrographs are presented in the SWHC 1995 Annual Report. All stream-flow data presented as volume discharges rather than hydrographs.

Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Surface Water	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Properties (discharge, extent, storage) • SWHC 1995 Annual Report, Section 3.2.2 and Appendix A, Section A.4 (SNL/NM, 1996a)	**Flood Frequency Plots/Maps** • None	Properties information also presented in SWHC 1994 Annual Report, Appendix C, Section C.3 (SNL/NM, 1995b) and Calendar Year 1996 Annual Groundwater Monitoring Report, Section 2.3 (SNL/NM, 1997). Flood prone areas are presented in the SWHC 1992 Annual Report, Fig 4-3 (flood prone areas) and Table 4-1 (peak discharges during flooding) (SNL/NM, 1993). Other flood frequency information is presented in: Bovay Engineers (1981) and Leedshill-Herkenhoff (1987) drainage management plans for Tijeras Arroyo; Bohannan-Huston (1992), drainage system analysis for TA-I, TA-II, and TA-IV; McCann and Boissonnade (1988), flooding potential at SNL/NM; U.S. Corps of Engineers (1979), flood hazard analysis.

Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Surface Water	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Relationship to Groundwater • Geology Report, Section 2.1.2 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Appendix A, Section A.7 (SNL/NM, 1996a)	**Gain/Loss Plots** • None	Gain/loss plots are generated from seepage runs on flowing streams - no such streams exist on SNL/KAFB land.
		Longitudinal channel profile • Geology Report, Fig 2.1-10g (Arroyo del Coyote) (SNL/NM, 1995a)	
		Channel cross section(s) • Geology Report, Tijeras Arroyo: Figs 2.1-5 (a and b) through 2.1-7; Arroyo del Coyote: 2.1-9, 2.1-10 (a through f), 2.1-12, and 2.1-14 (a through c), (SNL/NM, 1995a) • SWHC 1995 Annual Report, Appendix A, Fig A-4 (SNL/NM, 1996a)	
		Water quality table(s) • SWHC 1995 Annual Report, Appendix A, Table A-3 (SNL/NM, 1996a)	More data, including surface and groundwater quality, are available in annual Site Environmental Reports (e.g. SNL/NM, 1996b) and the background concentration study (SNL/NM, 1995c).

Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Soil Water	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Thickness of the Vadose Zone • SWHC 1995 Annual Report, Sections 3.2.3 and 3.2.3.1 (SNL/NM, 1996a)	**Hydrogeological setting and flow paths** • SWHC 1995 Annual Report, Fig 3.2.2-1 (SNL/NM, 1996a)	
	Moisture Content • SWHC 1995 Annual Report, Sections 3.2.3 and 3.2.3.1 (SNL/NM, 1996a)	**Maps - i.e. thickness of the vadose zone, average moisture content, moisture at a certain depth, average maximum concentration of a solute at a given depth** • Geology Report, Figs 2.1-12, 2.1-16, and 2.1-23 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Fig 3.2.2-1 and Table 3.2.4-6 (SNL/NM, 1996a)	Other moisture content information are available in Roepke et al (1996), Goering et al (1996), DBS&A (1989). Thickness of the vadose zone east of the fault complex can be obtained by combining Plate XI of the Geology Report (SNL/NM, 1995a) and the potentiometric surface map (Plate IV) of the SWHC 1995 Annual Report (SNL/NM, 1996a) and topographic maps. Information on the range of vadose zone thickness is given in Section 3.2.3 of the SWHC 1995 Annual Report (SNL/NM, 1996a).

Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Soil Water	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Solute Chemistry • None		Typical native soil-water content is far too low to extract water using standard techniques. Summaries of chemical analyses performed on bulk soil samples are available in the background concentration study (SNL/NM, 1995c). These analysis include the precipitated form of soluble species contained in soil water.
Groundwater	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Characteristics of Hydrologic Units - lithology, extent, etc • Geology Report, Sections 3.1, 3.2, 4.1,and Appendix B (SNL/NM, 1995a) • SWHC 1995 Annual Report, Sections 3.2.4 and 4.2.2 (SNL/NM, 1996a)	**Well Construction Diagrams** • SWHC 1995 Annual Report, Appendices C and D (SNL/NM, 1996a)	Summary well records are presented in the 1995 Annual Groundwater Monitoring Report - Appendices A and B (SNL/NM, 1996d). Complete SNL/NM well files, including well construction diagrams, are maintained in two places. Hard copy files are maintained at the ES&H Records Center. Electronics records are maintained in the ERDMS which runs on Oracle on a Sun platform.

Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Groundwater	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Scale - Regional or perched • Geology Report, Sections 3.1.3, 3.2.3, and 4.1 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Sections 3.2.4.1, 3.2.4.2, and 3.2.4.3 (SNL/NM, 1996a)	**Water Depth Maps/Tables - depth of first water, selected perched zone(s), regional water table** • SWHC 1995 Annual Report, Tables 3.2.4-6, and 3.2.4-7 (SNL/NM, 1996a)	Water level maps and data are also available in the 1996 Annual Groundwater Monitoring Report - Figs 41 and 42, and Tables A1 through A35 (SNL/NM, 1997). More detailed discussions on the shallow groundwater system in the vicinity of Tijeras Arroyo near TA-II are available in SNL/NM, 1994 (Section 5.6); SNL/NM, 1995b (Appendix L); SNL/NM, 1996c; and Fritts and Van Hart, 1997. West of the fault complex, water depth for the regional water table and the perched zone in the vicinity of Tijeras Arroyo can be determined by using topographic maps and Plate IV from the SWHC 1995 Annual Report, (SNL/NM, 1996a). East of the fault complex, the piezometric heads for the uppermost aquifer unit and the elevation of the first occurance of bedrock are are mapped on Plates XV and XVI of the SWHC 1995 Annual Report, (SNL/NM, 1996a).

Major Model Element - Hydrology			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Groundwater	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Water quality - background/contaminated values for general chemistry, major ions, metals, radionuclides; variations across the area • Site-Wide Geochemical Report, (DOEAL/GJPO, 1995) • SWHC 1995 Annual Report, Section 3.2.4.3.5 (SNL/NM, 1996a)		Other information on groundwater quality is available in the 1996 Annual Groundwater Monitoring Report, Sections 5.0 and 6.0, (SNL/NM, 1997) and the Background Concentration Study, (SNL/NM, 1995c)
	Water Budget • [Recharge] SWHC 1995 Annual Report, Sections 3.2.2.1, 3.2.4.3.5, and 4.2.1; Appendix A - Sections A.7 and A.8; and Appendix B, Section B.3.6 (SNL/NM, 1996a) • [Discharge] Geology Report, Section 2.2.3 (SNL/NM, 1995a) • [Discharge] SWHC 1995 Annual Report, Section 4.2.1 (SNL/NM, 1996a) • [Modeling] SWHC 1995 Annual Report, Section 3.2.5 and Appendix E (SNL/NM, 1996a)		No explicit water budget was evaluated. An integrated estimated water budget was added to the SWHC 1995 Annual Report (Revised February 1998) in Section 4.1.2.8. In addition, the final SWHC 1995 Annual Report will include an update on groundwater modeling.

BASIC ELEMENTS OF THE SNL/NM SITE-WIDE HYDROGEOLOGIC CONCEPTUAL MODEL			
Major Model Element - Synthesis			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Groundwater	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Flow - direction, rate gradient • Geology Report, Sections 3.1.3 and 3.2.2 (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 3.2.4.3.3 (SNL/NM, 1996a)	**Water Quality Maps - concentration contours** • None	At the site-wide scale, water quality data are too sparse to provide meaningful contours.
	Discharge - area, mechanism, rate • Geology Report, Sections 2.2.3 (springs) (SNL/NM, 1995a) • SWHC 1995 Annual Report, Section 4.2 (SNL/NM, 1996a)	**Water Quality Diagram(s) - Piper, Stiff, etc.** • Site-Wide Geochemical Report, Figs 4-4, 4-5, 4-6, 4-7, 4-8, 4-9, 4-10, 4-12, 4-13, 5-1,and 5-3; Appendices C and D (DOEAL/GJPO, 1995)	Most groundwater discharge from the KAFB area occurs at KAFB and City of Albuquerque water supply production wells. Information on KAFB water well production is presented in the SWHC 1992 Annual Report, Section 4.4.2 (SNL/NM, 1993a). Other water quality diagrams are presented in the SWHC 1992 Annual Report, Figs 4-21, 4-22, 4-23; Tables 4-10 and 4-11 (SNL/NM, 1993a)

Major Model Element - Synthesis			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Conceptual Hydrogeologic Model	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Water budget for area • [Recharge] SWHC 1995 Annual Report, section 4.2, Appendix A - Sections A.7 and A.8, and Appendix B, Section B.3.6 (SNL/NM, 1996a) • [Discharge] SWHC 1995 Annual Report, Section 4.2 (SNL/NM, 1996a) • [Modeling] SWHC 1995 Annual Report, Section 3.2.5 and Appendix E (SNL/NM, 1996a)	**Geologic Map at the Water Table - geologic and hydrologic units, water level contours, flow direction(s), water quality zones** • Geology Report, Plate XI (SNL/NM, 1995a) • SWHC 1995 Annual Report, Figs 3.2.4-2, 3.2.4-3, and 3.2.4-4 and Plates III and IV (SNL/NM, 1996a)	No explicit water budget was evaluated. We will incorporate an integrated estimated water budget into the SWHC 1995 Annual Report in Section 4.1.2.8 in response to the documented Notice of Deficiencies. A draft of this integrated water budget is included as an attachment to this working list. In addition, the final SWHC 1995 Annual Report will include an update on groundwater modeling.
	Hydrochemical facies • Site-Wide Geochemical Report, (DOEAL/GJPO, 1995) • SWHC 1995 Annual Report, Section 3.2.4.3.5 (SNL/NM, 1996a)		.

Major Model Element - Synthesis			
Sub-element	**REFERENCE LOCATION IN SITE-WIDE 1995 ANNUAL REPORT (INCLUDING THE ATTACHED GEOLOGY REPORT AND GROUNDWATER GEOCHEMICAL REPORT)**		
Conceptual Hydrogeologic Model	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**
	Geologic controls of hydrologic phenomena • Geology Report, Section 4.1 (SNL/NM, 1995a) • SWHC 1995 Annual Report, [Soil water holding capacity impacts on recharge] Section 4.1.2.3 and 4.1.2.8; [faults] - 4.2.2.2.4;[perched aquifer] - Section 4.2.2.1.3; [ancestral, incised channels beneath ITRI] - Section 4.2.2.3.1 (SNL/NM, 1996a)		
Hydrogeologic Report	**INFORMATION**	**ILLUSTRATIONS**	**OTHER REFERENCES AND COMMENTS**

The synthesis of information and illustrations for the major elements and sub-elements identified in this table are primarily contained in the Site-Wide Hydrogeologic Characterization 1995 Annual Report (SNL/NM, 1996a)and its attached reports (1) Conceptual Geologic Model of the Sandia National Laboratories and Kirtland Air Force Base [identified as Geology Report in the above table] (SNL/NM, 1995a) and (2) Groundwater Geochemical Study of Groundwater at Sandia National Laboratories/New Mexico and Kirtland Air Force Base [identified as the Geochemical Report in the above table] (DOE/GJPO, 1995).

References

Bohannan-Huston, Inc., 1992. Storm Drain Master Plan for Areas I, II, and IV, Sandia National Laboratories, Albuquerque, NM.

Bovay Engineers, Inc., 1981. Tijeras Arroyo Drainage Management Plan. Albuquerque Metropolitan Arroyo Flood Control Authority, Albuquerque, NM.

DBS&A, 1989. Laboratory Analysis of Soil Hydraulic Properties from Chemical Waste Landfill CAP Verifications Project. Daniel B. Stephens and Associates, Albuquerque, NM.

DOEAL/GJPO, 1995. Geochemical Study of Groundwater at Sandia National Laboratories/New Mexico and Kirtland Air Force Base. U.S. Dept. of Energy Albuquerque Operations Office and Grand Junction Projects Office, Grand Junction, Colorado. Produced by Rust Geotech under DOE contract DOE-AC04-94AL96907. (Included as Attachment 2 to SNL/NM 1996a).

Fritts, J.E. and D. Van Hart, 1997. Sandia North Geologic Investigation Project Report. Gram Inc., Albuquerque, NM.

Goering, T., M. D. McVey, W. R. Strong, and J. L. Peace, 1996. Analysis of Instantaneous Profile Test Data from Soils Near the Mixed Waste Landfill, Technical Area 3, Sandia National Laboratories/New Mexico. Sandia Report SAND95-1637 UC-903, February, 1996.

Hacker, L., 1977. Soil Survey of Bernalillo County and Parts of Sandoval and Valencia Counties, New Mexico. USDA Soil Conservation Service, U.S. Dept. Interior Bureau of Land Management, and New Mexico Ag. Exp. Station.

Leedshill-Herkenhoff, Inc., 1987. Tijeras Arroyo Drainage Management Plan, Phase I: City of Albuquerque, Albuquerque, NM.

McCann, M. W., and A. C. Boissonnade, 1988. Natural Phenomena Hazards Modeling Project: Preliminary Flood Hazards Estimates for Screening Department of Energy Sites. D.O.E. Albuquerque Operations Office, Lawrence Livermore National Laboratory, University of California, Livermore, CA.

Roepke, C. S., W. R. Strong, H. A. Nguyen, M. D. McVey, and T. Goering, 1996. Unsaturated Hydrologic Flow Parameters Based on Laboratory and Field Data for Soils Near the Mixed Waste Landfill, Technical Area III, Sandia National Laboratories/New Mexico. Sandia National Laboratories Report SAND96-2090 UC-903, August, 1996.

Roepke, C.S., 1997. Personal Communication.

SNL/NM, 1993. Site-Wide Hydrogeological Characterization Project, Calendar Year 1992 Annual Report. SNL/NM ER Project, Albuquerque, NM.

SNL/NM, 1994. Site-Wide Hydrogeological Characterization Project, Calendar Year 1993 Annual Report. SNL/NM ER Project, Albuquerque, NM.

SNL/NM, 1995a. Conceptual Geologic Model of the Sandia National Laboratories and Kirtland Air Force Base. SNL/NM ER Project, submitted by GRAM, Inc., December, 1995. (Included as Attachment 1 to SNL/NM 1996a).

SNL/NM, 1995b. Site-Wide Hydrogeological Characterization Project, Calendar Year 1994 Annual Report. SNL/NM ER Project, Albuquerque, NM.

SNL/NM, 1995c. Background concentrations of constituents of concern. SNL/NM Environmental Restoration Program, Albuquerque, NM.

SNL/NM, 1996a. Site-Wide Hydrogeological Characterization Project, Calendar Year 1995 Annual Report. SNL/NM ER Project, Albuquerque, NM.

SNL/NM, 1996b. 1995 Site Environmental Report. Sandia National Laboratories, Albuquerque, New Mexico.

SNL/NM, 1996c. Hydrologic Characterization of a Perched Aquifer near TA-II / Tijeras Arroyo: Estimating Travel Times, and Possible Sources of Recharge in the Perched Zone. SNL/NM ER Program, Site-Wide Hydrogeologic Characterization Project, Albuquerque, NM. Draft report prepared by R. Wolford of GRAM, Inc., Albuquerque, NM, September, 1996.

SNL/NM, 1996d. Groundwater Protection Program Calendar Year 1995 Annual Groundwater Monitoring Report, Sandia National Laboratories/New Mexico. Groundwater Protection Program, SNL/NM, Albuquerque, NM.

SNL/NM, 1997. Groundwater Protection Program Calendar Year 1996 Annual Groundwater Monitoring Report, Sandia National Laboratories/New Mexico. Groundwater Protection Program, SNL/NM, Albuquerque, NM.

U.S. Army Corps of Engineers, 1979. Special Flood Hazard Information, Tijeras Arroyo and Arroyo del Coyote, Kirtland AFB, New Mexico. U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

Response to EPA's draft "Evaluation of SNL Response to EPA Comments on the 1994 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Response to EPA's draft "Evaluation of SNL Response to EPA Comments on the 1994 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
		GENERAL COMMENTS		
1.	Individual conceptual models are advanced for specific study areas, but results of these studies have not been integrated or applied on a site-wide basis. The Site-Wide Hydrogeologic Characterization (SWHC) Report should include additional discussion summarizing the site-wide hydrogeologic regime and indicating how the results of the newer studies apply on a site-wide basis.	Comment acknowledged; will be addressed in 1995 SWHC Report.	Yes	Section 4.0 of 1995 SWHC Report was revised to present a site-wide conceptual model.
Response	Comment acknowledged			
2.	The 1994 SWHC report should be revised to include additional appendices that present the results of the studies discussed in Section 2.2 through 2.10 in more detail.	The SWHC Project does include all known pertinent information from reports of work on the hydrogeology of the facility in the SWHC Report.	Yes	None.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Response to EPA's draft "Evaluation of SNL Response to EPA Comments on the 1994 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
3.	The method presented for regional saturated zone modeling is apparently still under development. The "standard" MODFLOW and MODPATH may provide sufficient regional understanding of groundwater flow and particle movement.	Appendix G, in which the modeling approach was presented, was withdrawn.	Yes	1995 SWHC Report includes site-wide saturated zone model using a modified version of MODFLOW.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
4.	Revise the 1994 SWHC report to include a table summarizing data gaps and anticipated activities and dates for resolution of these data gaps.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	No[1]	Conceptual model uncertainties and related data gaps are identified in Tables 4.3-1, 4.3-2, and 4.3-3. However, these tables do not present the dates to resolve data gaps.
Response	*Revise the 1995 Annual Report as follows:* *(a) Place an "*" at the end of the captions of Tables 4.3-1, 4.3-2, and 4.3-3, and the following footnote at the base of each table:* * The SWHC Project has no plans to collect additional data or to reduce the uncertainties identified in this table. *(b) Add the final closing paragraphs to Section 4.3, following Table 4.3-3:* The objective of the SWHC Project was to determine the generalized, overall regional framework of geology, hydrology, and hydrogeology which together determine the regional flow patterns of water and, by extension, flow patterns of contaminants that may be transported by that water. This report meets that objective and completes the SWHC Project. No additional field work or data analysis, including those described as providing "useful additional data" in Tables 4.3-1 and 4.3-3, has been planned for the SWHC Project. SNL/NM task leaders and regulators for individual sites may make determinations on the need to collect any "useful additional data" which are deemed necessary to complete a site-specific evaluation.			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Response to EPA's draft "Evaluation of SNL Response to EPA Comments on the 1994 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
5.	Technical statements in SWHC report require more adequate referencing. Please review 1994 SWHC report to ensure that factual statements are adequately referenced.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	Factual statements throughout the 1995 SWHC Report are well referenced
Response	Comment acknowledged			
6.	Include schedule for completion of tasks for the annual SWHC report.	The tasks presented were completed by end of the calendar year of the report.	Yes	None.
Response	Comment acknowledged			
7.	Have Data Quality Objectives (DQOs) been prepared for the SWHC project?	Comment acknowledged and will be resolved within an explanation of the technical approach of the project in the next report.	No[1]	Page –12 of the SWHC Report indicates that the DQO process is included in the approach, but this approach is not reflected in the explanation presented within the text.
Response	***The DQO Process was explained in Section 1 of the 1995 Annual Report.***			
8.	Complete potentiometric surface maps should be prepared for the facility area.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	Potentiometric surface map presented in Plate IV of 1995 SWHC Report
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Response to EPA's draft "Evaluation of SNL Response to EPA Comments on the 1994 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
9.	Presentation of water level and geochemical data should include month/day/year.	Comment acknowledged; will be addressed in 1995 SWHC Report.	Yes	Included in Attachment 2 of the 1995 SWHC Report.
Response	Comment acknowledged			
		SPECIFIC COMMENTS		
SECTION 1.0 INTRODUCTION				
1.2 The SWHC Project and the ER Project at SNL/NM (pp. 1-1 to 1-8)				
1.	Revise the 1994 SWHC report to include a very brief discussion regarding how the operating unit (OU) sites presented in Table 1.2.1 were prioritized using the DOE Priority System.	A brief comment will be added to the 1995 SWHC Report which explains how the prioritization results are applied by the environmental restoration (ER) Project. For more discussion on the Site Prioritization Paradigm, the reader will be directed to the Program Implementation Plan for Albuquerque Potential Release Sites.	No[1]	The priority ranking of each site is identified in Table 1.3-1 of the 1995 SWHC Report, but specifically how the sites were ranked is not included.
Response	***As stated by EPA how the sites were ranked is not included. Such a description is beyond the scope of the site-wide hydrogeologic conceptual model at SNL.***			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
2.	Present contaminant-specific (contaminant distribution) information in future SWHC reports when that information is useful in demonstrating hydrogeologic conditions or supports the conceptual model established for Sandia National Laboratories (SNL). Also indicate how necessary or pertinent information will be determined, and who, within the SNL organization, will determine whether this information will be integrated.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	No [1, 2]	Section 1.1 of the 1995 SWHC Report indicates that contaminant distribution information may appear in the report when that information is useful in demonstrating hydrogeologic conditions or when it supports conceptual models. However, specifically how this will be determined, and by whom, is not included.
Response	***Section 1.1 revised to address comment*** The HSWA Permit does not mandate the inclusion of all contaminant distribution information in the site-wide annual reports. However, hydrogeologic data gathered by the ER Project at individual sites has been included in our assessment of the site-wide hydrogeologic framework.			

SECTION 2.0 SUMMARY OF CALENDAR YEAR 1994 SNL/NM ER PROJECT CHARACTERIZATION ACTIVITIES

2.1 Site-Wide Hydrogeologic Characterization Project

2.1.1 1994 SWHC Project Activities and Investigations (pp. 2-1 to 2-5)

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
3.	Revise the report to include references to boring and monitoring well location maps.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The 1995 SWHC Report includes references to monitoring well location maps. Although boring location maps are not included, the references are sufficient in the context that they are presented. The SWHC Report was modified so significantly that the context in which the original comment was made is no longer valid. The SWHC Report has also been significantly revised to include numerous appendices and attachments that address the structural features more thoroughly.
Response	Comment acknowledged			

SECTION 3.0 – SITE-WIDE HYDROGEOLOGIC SETTING

3.1 Geology

3.1.1 Stratigraphy

3.1.1.2 Upper Paleozoic Strata (pp. 3-4 to 3-6)

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
4.	Additional information was requested regarding what information the steeply dipping bed data provided relative to the structural framework of the alluvium.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The SWHC Report was modified so significantly that the context in which the original comment was made is no longer valid. The 1995 SWHC Report includes numerous appendices and attach-ments that address the structural and strati-graphic features more thoroughly.
Response	Comment acknowledged			
3.1.1.5 Neogene/Quarternary Santa Fe Group Strata (pg. 3-7)				
5.	The report should be revised to correctly reference figures pertaining to cross sections within the Albuquerque Basin.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The SWHC Report has been modified so that the context in which the reference was made is no longer valid; the report, in general, adequately references most figures, tables, etc.
Response	Comment acknowledged			
3.1.2 Structural Geology (pg. 3-8)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
6.	Revise the SWHC report to correctly reference the hydrogeologic regions.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The SWHC Report has been modified so that the context in which the original comment was made is no longer valid. References to figures presenting the hydro-geologic regions are adequate.
Response	Comment acknowledged			
3.1.2.1 Regional Tectonic Setting (pp. 3-8 to 3-9)				
7.	Revise the report to include major fault locations upon Figure 3.1.1, or to reference more appropriate figures.	Comment acknowledged; will be addressed in the 1995 SWHC Report	Yes	The SWHC Report has been revised to appropri-ately reference maps that present fault locations.
Response	Comment acknowledged			
8.	References to both the Rio Grande Fault and Rio Grande Rift were confusing and clarification was requested.	Sandia acknowledged that the use of both terms could be confusing and future authors will try to avoid language that could lend to this confusion.	Yes	The geologic conceptual model in Attachment 1 is written so that the reader does not confuse the Rio Grande Rift and Rio Grande fault.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
3.1.3 Geomophology and Soils **3.1.1.2 Soils (pp. 3-15 to 3-16)**				
9.	Revise the report to correctly reference the hydrogeologic regions.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The 1995 SWHC Report includes sufficient and accurate references to figures presenting hydrogeologic regions.
Response	Comment acknowledged			
3.2 Hydrologic Setting **3.2.1 Meteorology (pp. 3-16 to 3-18)**				
10.	Since area is prone to flash flooding, additional justification requested for decision not to install additional rain gages and model rainfall/runoff relationships.	Comment acknowledged; will be addressed in 1995 SWHC Report.	Yes	Difficulty of further modeling rainfall/runoff relationships is discussed at length in Section 3.2.2 of 1995 SWHC Report.
Response	Comment acknowledged			
3.2.2 Surface Water (pp. 3-18 to 3-21)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
11.	Revise the 1994 SWHC Report to further discuss the applicability of the Santa Fe information to SNL and to indicate, if appropriate, whether site-specific information will be acquired.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	Surface water modeling, including applicability of Santa Fe water quality data and utility of further on-site surface water data collection, is discussed at length in Section 3.2.2 of the 1995 SWHC Report.
Response	Comment acknowledged			
12.	Revise the 1994 SWHC Report to clarify whether calculations for anticipated flood heights for local drainage will be adjusted/revised based tree trunk found above stream channel of Arroyo del Coyote.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The implications of the tree trunk found above the stream channel of Arroyo del Coyote is discussed at length in Section 3.2.2 of the 1995 SWHC Report.
Response	Comment acknowledged			
3.2.2.1 Arroyo-Groundwater Interactions (pp. 3-21 to 3-22)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
13.	Revise the 1994 SWHC Report to state whether additional study regarding arroyo recharge to groundwater is planned in the future and reference appropriate sections, as applicable.	Comment acknowledged; will be addressed in 1995 SWHC Report.	Yes	Additional studies of arroyo-groundwater interaction are discussed in Section 3.2.2.1 and Appendix A and B of the 1995 SWHC Report.
Response	Comment acknowledged			
3.2.3 Vadose Zone Hydrology **3.2.3.1 Vadose Zone Hydrogeologic Framework (pp. 3-23 to 3-27)**				
14.	Revise the 1994 SWHC Report to include a summary discussion of how the nine vadose zone hydrogeologic settings were determined, alternatively, refer to the appropriate document for discussion.	The appropriate document was referenced on page 3-27.	Yes	None.
Response	Comment acknowledged			
3.2.4.1.2 Hydrogeologic Region 2 (pg. 3-32)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
15.	The nature of groundwater flow associated with major faulting should be determined.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	Groundwater flow across fault discussed in Section 3.2.4.3.3 and Attachments 1 and 2 of the 1995 SWHC Report. Interpretations within these reports indicate that efforts have been made to assess groundwater flow associated with major faulting using aquifer parameters, geologic information, and geo-chemical data. Although data gaps are apparent, the presentation of groundwater flow in faulted areas is significantly improved when compared to previous reports, and is adequate because the effort was made to provide a more complete interpretation of the system using available data.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
SECTION 4.0 HYDROGEOLOGIC CONCEPTUAL MODEL				
16.	The 1994 SWHC dose not include a sufficiently comprehensive or integrated site wide conceptual model. Revise Chapter 4 of the 1994 SWHC Report to include a more comprehensive site-wide conceptual model in which site-specific information is fully integrated.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	Chapter 4.0 of the 1995 SWHC Report has been revised to include a reasonably comprehen-sive site-wide model that integrates the site-specific information.
Response	Comment acknowledged			
4.3 1994 Conceptual Model of the Hydrogeologic Environment of the SNL/KAFB Area **4.3.3 High Groundwater Elevation Along the South Fence Road: Alternative Models (pp. 4-20 to 4-24)**				
17.	The comment requested that the text discuss the significance of water level head variation and groundwater geochemistry in the MWL and CWL.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	Groundwater flow path and geochemical data analyses for the SNL/ KAFB wells is presented in Attachment 2.
Response	Comment acknowledged			
4.3.4 Area Where Shallow Alluvial Aquifer May be Controlled by the Buried Bedrock Surface (pg. 4-24)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
18.	The comment asked for elaboration regarding how the paleotopographic model for the ITRI would be used on a regional basis. Requested that the text discuss the significance of water level head variation and groundwater geochemistry in the MWL and CCL.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	No[3]	Attachment 2 presents groundwater chemistry data and interpretations. The 1995 SWHC Report and associated appendices do not attempt to apply paleotopographic data on a regional basis (although still applied on a site-specific basis).
Response	***Section 4.2.2.3.1 revised to discuss the limitations of the paleotopographic model*** Where the top of the saturated zone is within the alluvial fill of paleochannels at ITRI, the paleochannels control flow directions (Attachment 1, Figure 4.0.1). It is possible that a buried paleochannel extending northeast from ITRI may connect subsurface flows from the Arroyo del Coyote/Coyote Springs area to flows from EOD Hill and ITRI (Attachment 1, Figure 4.0.1). Paleotopographic data used to generate the paleotopographic model are only available in the area where bedrock exists at shallow depths. That situation exists only east of the "fault complex." The model is best demonstrated in the ITRI area, where there are more than 30 closely-spaced wells providing subsurface control points. Northwest, north and northeast of ITRI, the model can be applied using several rock outcrops, refraction seismic data, but only six wells; these data points result in the mapping of other, less clearly defined paleochannels. We incorporated the flow effects from these channels, in connection with a piezometric surface map, into a flow-directional model (see Section 3.2.4.3.3 and Figure 3.2.4-3). The paleodrainage model is not applicable west of the fault complex because there are no wells known to encounter bedrock.			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
APPENDIX D **D.3 Methodology** **D.3.3 Input Parameter Ranges and Distribution (pp. D-6 to D-9)**				
19.	Discuss more thoroughly the values of dispersivity acquired through the Electric Power Research Institute Report and the applicability to SNL/KAFB.	Because site-specific dispersivity values were not available, a broad range of values in unsaturated media was selected which encompass values appropriate for the SNL/KAFB area. The dispersivity values used in the modeling were taken from several sources including the Electric Power Research Institute (Gelhar et al., 1985), McCord and Goodrich (1995), and Quantitative Hydrogeology: Groundwater Hydrology for Engineers (de Marsily, 1986).	Yes	None.
Response	Comment acknowledged			
20.	Table D.1 on page D-8 includes footnote superscripts which have not been used to identify any items in the table.	Table D.1 has been reprinted. Footnote a has been changed to reference Gelhar et al. (1985), McCord and Goodrich (1995) and de Marsily (1986) (see response to 19 above). Footnote b, c, and d are not needed and have been removed from the bottom of the table.	Yes	None.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
D.4 Monte Carlo Simulation Results **D.4.1 Performance Measure (pg. D-9)**				
21.	The discussion of performance measures implies that the water table performance measure was selected with cost as a consideration. However, absolute cost may not be the deciding criteria for these measures.	Please see attached revision to Section 4.3.4, paragraph 4.	Yes	Revised text addresses concern identified in the text.
Response	Comment acknowledged			
D.5 Summary and Conclusions (pg. D-19)				
22.	Define in more precise terms what is meant by small spill in paragraph 3 on page D-19 where it is stated that dispersivity is an important parameter for contaminant movement and distribution associated with very small spills.	As described on this page, a small spill is considered to be the result of a short duration (a few days), low discharge rate (a few gallons per day) spill or leak from a tank or pipeline. Sandia does not intend to be specific or quantitative because it is presenting a generic model that can be applied to an actual field spill. Sandia was not describing an actual field release situation.	Yes	None.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
APPENDIX F **F.3 Application of MODFLOW to SNL/NM Hydrogeologic Region 1** **F.3.1 HR-1 Domain Discretization and Boundary Conditions (pp. F-6 to F-9)**				
23.	The text states that a total of 17 observation points have been used as internal head values in the computation of the objective function. However, head values for only 15 wells are identified. Resolve this apparent discrepancy, and provide a map identifying the location of each well and the water level contours resulting from these data throughout the model domain.	(a) As stated in the text, (page F-9) seventeen observation points were used as internal head values for computation of the objective function. Note, however, the footnote to Table F.1 which indicates that the head values present for the Chemical Waste Landfill, KAFB-0308 and 0309, the Golf Course, and the Mixed Waste Landfill represent the average head for a number of wells at each site, thus Table F-9 lists only 15 head measure-ments. During inverse modeling, the three Golf Course wells were included as separate data points. (b) Figure 5.6.16 (B) from the SWHC 1993 Annual Report provides a well location and water level contour map for the head values used in the inverse modeling. That figure is reproduced and attached here for your reference.	Yes	None
Response	Comment acknowledged			
F.3.2 Hydrologic Parameter Fitting (pg. F-9)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
24.	Table F.2 on page F-9 presents the conceptual model zoning and estimated parameters. Revise the table to present Case 3, if applicable. In addition, Case 2 references Figure F.3b; however, this figure was not included in this appendix. Revise the appendix to include Figure F.3b.	See attached revised Table F.2.	No[1]	While revised Table F.2 include Case 3, Figure F.3b was not provided. However, discussion of the conceptual model has been significantly improved and appears to be sufficient except as noted in Deliverable 2.
Response	***Latest modeling discussion and results are included in new Attachment 4 to the 1995 Annual Report.***			
25.	The three different transmissivity zones depicted in Figure F.5 do not appear to account for the Ancestral Rio Grande deposits discussed in Appendix G. How was this feature accounted for in this modeling effort? Discuss the potential impact of such a feature on the transmissivity values identified in this modeling effort and on the anomalously high water levels studied in this modeling effort.	In actuality, the ancestral Rio Grande deposits are accounted for in both Cases 2 and 3. The higher permeability/ transmissivity zone to the west discussed on pages F-10 and F-11 is associated with the axial channel deposits of the ancestral Rio Grande. See the first paragraph of Section F.3.2.2.	Yes	None.
Response	Comment acknowledged			
F.3.2.2	**Inverse solution for Multiple Transmissivity Zones (pp. F-10 to F-12)**			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
26.	An apparent modification of a three-transmissivity zone model to address the over prediction of heads near the northern portion of TA-III and V is discussed. This modification may account for the Case 4 presented in Table F.5. Clarify whether, in fact, four different cases were evaluated.	See responses to Specific comments 24 and 25.	Yes	The previous revisions make clear that only three cases were evaluated.
Response	Comment acknowledged			
APPENDIX G **G.1 Introduction (pg. G-1)**				
27.	No rationale has been provided for the eight general limitations on the conditional stochastic model that were identified as the most important limitations to be removed or assessed.	We have retracted Appendix G per General Comment 3. Comments acknowledged and may be incorporated into any future DOE studies.	Yes	See General Comment 3.
Response	Comment acknowledged			
G.2 Approximations to Incorporate Well Effects (pp. G-1 to G-12)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
28.	The groundwater mound previously discussed is not included in the stochastic model. Discuss the impact that the non-inclusion of the groundwater mound may have on modeled results, assumptions, etc.	We have retracted Appendix G per General Comment 3. Comments acknowledged and may be incorporated into any future DOE studies.	Yes	See General Comment 3.
Response	Comment acknowledged			
G.5 Anisotropic Composite Media (pp. G-27 to G-37)				
29.	The discussion indicated that the modeling supports the occurrence of a relatively thin flow "channel" that would funnel contaminants northward with little or no lateral spreading. Include additional information regarding the occurrence of this channel, referencing additional appendices or forthcoming studies that will address this.	We have retracted Appendix G per General Comment 3. Comments acknowledged and may be incorporated into any future DOE studies.	Yes	See General Comment 3.
Response	Comment acknowledged			
APPENDIX H **H.4 Summary of 1994 Drilling Operations** **H.4.5 Powerline Wells PL-1, PL-2 and PL-3 (pg. H-23)** **H.4.5.1 Drilling Operations (pp. H-23 to H-24)**				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
30.	The discussion indicated that the modeling supports the occurrence of a relatively thin flow "channel" that would funnel contaminants northward with little or no lateral spreading. Include additional information regarding the occurrence of this channel, referencing additional appendices or forthcoming studies that will address this issue.	We have retracted Appendix G per General Comment 3. Comments acknowledged and may be incorporated into any future DOE studies.	Yes	See General Comment 3.
Response	Comment acknowledged			
APPENDIX I **I.2 Test Equipment (pg. I-2)**				
31.	Clarification regarding error introduced by using Solinist water level tapes was requested.	Sandia responded by attaching a revision to the questioned text that indicated that the error was no more than .02 feet.	Yes	None.
Response	Comment acknowledged			
I.3 SFR-3 Location Tests **I.3.1 SFR-3T Pumping Tests (pg. I-4)**				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
32.	Clarification was requested regarding whether monitoring well SFR-3S was monitored during the SFR-3T pumping tests.	Sandia responded by attaching a revision to the questioned text which indicated, twice, that SFR-3P (not SFR-3S) did not show any response to the pumping test at SFR-3T.	No[1]	Apparently, the response included an error in that it listed SFR-3P twice. It is assumed that SFR-3S was intended to be listed instead of the dual listing of SFR-3P; if this is the case, the response to the comment is sufficient.
Response	***This was a typographical error in the 1994 Annual Report and is not reflected in the 1995 Annual Report.***			
I.3.1.1 SFR-3T Pumping Test Data Analysis (pp. I-4 to I-14)				

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
33.	Justification for using the Cooper Jacob method was requested, as well as a listing of alternative methods considered (if any alternatives were considered).	Sandia responded by attaching a revision to the questioned text which stated that the accuracy of the Cooper Jacob method was sufficient for this study, and other alternative methods were laborious and "any additional accuracy that they might provide would not be significant."	No[1]	The response does not directly address the comment, in that the specific alternative considered were not listed and detailed discussion regarding why the Cooper-Jacob method was selected is not included. However, the Cooper Jacob method typically yields adequate data and is often used to evaluate data of this nature. The argument that other methods are "too laborious" is not necessarily accurate, since many computer codes exist that make the use of other methods relatively simple. It is, however, not necessarily important to the quality of the report or analytical results that additional methods be performed or considered, since the Cooper-Jacob method

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
				can yield sufficient results.
Response	*Identified as minor issue with no impact on the quality of the report. No revisions have been made to respond to this comment*			
I.6 Summary and Conclusions (pg. I-22)				
34.	The comment requested revision of the text to discuss the apparent lateral continuity of a low hydraulic conductivity unit at the CWL and MWL areas.	Sandia responded by attaching a revision to the questioned text which indicated that available data are insufficient to conclude whether or not the low hydraulic conductivity interval is continuous between the CWL and MWL areas.	Yes	None.
Response	Comment acknowledged			
APPENDIX K **K.3 Santa Fe Group Hydrogeology** **K.3.1 SFR-1 Santa Fe Group Hydrogeology (pg. K-5)**				
35.	The comment requested that the appendix be revised to indicate all the types of geophysical logs run in each of the wells that were logged.	Sandia responded by attaching a table which presented the types of geophysical logs run in five wells installed in the South Fence Road project area.	Yes	None.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
36.	The comment requested that a key be added to figures K.2 – K.4.	Sandia responded by attaching revised figures that included the requested key.	Yes	None.
Response	Comment acknowledged			
K.3.3 FRS-3 Santa Fe Group Hydrogeology (pp. K-6 to K-11) **K.3.5 SFR Project Area Santa Fe Group Hydrogeology (pp. K-12 to K-17)**				
37.	The comment asked for clarification why the SFR-3D location did not respond to the aquifer test conducted at SFR-3P, since the text indicated that the two were completed in the same hydrostratigraphic unit.	Sandia responded by attaching revised text which stated that the reason SFR-3D did not respond (if both SFR-3D and SFR-3S are within the same hydrostratigraphic interval) is because SFR-3D is completed within a portion of the unit that exhibits low vertical hydraulic conductivity.	No[1]	The response provided two alternatives, one of which called for completion of SFR-3S and SFR-3D in the same aquifer unit, but with differing vertical hydraulic conductivities at each. This alternative would imply, however, that Sandia should reconsider whether the entire interval should be considered a single hydrostratigraphic unit if one of the intervals has sufficiently low vertical hydraulic conductivity to affect pumping test response. Although not critical for the overall

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
				hydrogeologic conceptual model, this possibility should be kept in mind for site-specific assessments.
Response	***Identified as minor issue and not critical to overall hydrogeologic conceptual model. No revisions have been made to respond to this comment.***			
38.	The comment requested that Figure K.6 be revised to include MW-6, or to relabel MW-8 if it should be MW-6.	Sandia responded by attaching a Figure K.1 which showed the location of MW-6.	Yes	None.
Response	Comment acknowledged			
K.4 Bedrock Hydrogeology **K.4.4 SFR Project Area Bedrock Hydrogeology (pp. K-22 to K-23)**				
39.	The comment asked that the text be revised to discuss whether the Hubbell Springs Fault separates the completion intervals in SFR-4 and SFR-3T, and any inferences that can be made based upon water level data.	Sandia responded by attaching revised text that indicated: SFR-4 and SFR-3T were completed in the same general hydrostratigraphic unit; SFR-3T is completed "below" (not within) the Hubbell Springs Fault; and water level data from both wells show a low downward vertical gradient which suggests that the two wells are completed in a single hydrogeologic unit.	Yes	None.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
APPENDIX M				
40.	The comment requested that rough potentiometric surface contours be added to the maps in Hydrogeologic Regions 2 and 3.	Sandia responded by including water level maps (e.g. Figure 3.2.4-3, Plate IV) which presented water level contours drawn across the entire facility.	Yes	The intent of the comment was addressed with the inclusion of more detailed potentio-metric surface maps.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
M.6 Potentiometric Surface Map of the Upper Santa Fe Group (pg. M-6)				
41.	The comment requested that studies to assess the nature of the saturated zone be specified, as well as where data from these studies will be obtained, be included in the report.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	No[3]	Although generalized lists of data gaps for each Hydrogeologic Region are presented in Tables 4.3-1 through 4.3-3, the 1995 SWHC does not include a listing of specific studies that will be performed in the future, nor are specific locations within Hydrogeologic Regions cited where data will be collected. It is inferred that this information will be collected, as needed, during site/area-specific assessments.
Response	*Revise the 1995 Annual Report as follows:* *(a) Place an "*" at the end of the captions of Tables 4.3-1, 4.3-2, and 4.3-3, and the following footnote at the base of each table:* * The SWHC Project has no plans to collect additional data or to reduce the uncertainties identified in this table.			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Comment Number	Comment Summary	Sandia's Response	Response Adequate (Yes/No)	Additional Comments
	(b) Add the final closing paragraphs to Section 4.3, following Table 4.3-3: The objective of the SWHC Project was to determine the generalized, overall regional framework of geology, hydrology, and hydrogeology which together determine the regional flow patterns of water and, by extension, flow patterns of contaminants that may be transported by that water. This report meets that objective and completes the SWHC Project. No additional field work or data analysis, including those described as providing "useful additional data" in Tables 4.3-1 and 4.3-3, has been planned for the SWHC Project. SNL/NM task leaders and regulators for individual sites may make determinations on the need to collect any "useful additional data" which are deemed necessary to complete a site-specific evaluation.			
PLATES				
42.	The comment requested that Plates III and IV meet at the match line, and that the legend on Plate IV include a brief definition of maps units.	Comment acknowledged; will be addressed in the 1995 SWHC Report.	Yes	The 1995 SWHC Report has been so significantly revised relative to previous reports that the plates included in the current report are sufficient.
Response	Comment acknowledged			

1 – Response inadequate, but is a minor issue.
2 – Sandia has committed to include the necessary information, but without specifying an organization/role to address this, it is possible that this activity will not occur.
3 – Comment included in the review of the 1995 Site-Wide Report.

Response to EPA's draft "EPA Comments on the SNL 1995 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Response to EPA's draft "EPA Comments on the SNL 1995 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Section or Subject	Comment
GENERAL COMMENTS		
1.	General Comment: The 1995 Site-Wide Hydrogeologic Characterization (SWHC) Report and the Geologic Conceptual Model	In general, the 1995 SWHC Report and the Geologic Conceptual Model included in Attachment 1 coincide, although some questions remain (refer to Comment No. 5). However, as additional information is obtained as part of the SWHC project or other environmental restoration (ER) projects, refinement of either the SWHC hydrogeologic conceptual model or geologic conceptual model should be required. While it may be impractical to modify the geologic conceptual model, forthcoming revisions to the site-wide hydrogeologic model should indicate whether data impact the site geologic conceptual model so that those using either (or both) references will understand that changes to the model have been identified.
Response	***SNL/NM will request a permit modification to the HSWA permit to recommend that the 1995 Annual Report (with revisions discussed in this response) is the Final Report of the Site-Wide Hydrogeologic Characterization Project. The permit modification request will include language that leaves the door open to requests for future report revisions in case significant changes to the conceptual model are discovered.***	

Response to EPA's draft "EPA Comments on the SNL 1995 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Section or Subject	Comment
		SPECIFIC COMMENTS
2.	3.2.2.3 Role of the surface runoff in contaminant transport	The 1995 SWHC Report indicates that the risks posed by contaminant transport in surface runoff are minimized because there are no known sources of contamination in areas where severe erosion could occur, and there is no clear evidence of contamination within local surface runoff water. The 1995 SWHC Report goes on to state that "if such contamination were present in surface runoff, many contaminants would be retarded . . .when moving through soils. The retardation of contaminants by generally very thick vadose zones would suggest that much time may be required before some contaminants reach groundwater." These statements make broad inferences as to the mobility of contaminants at the site that are not supported by information presented in the 1995 SWHC Report. It is recommended that data to support the inferences presented in this section be included or referenced, or that this discussion and others of similar tone be removed entirely.
Response	***Section 3.2.2.3 has been revised to remove discussion on retardation of contaminant transport.***	
3.	3.2.4.3.3 Groundwater flow direction; flow across the faults	The 1995 SWHC Report states that similarities in conservative species water chemistry in four wells near the Tijeras fault system support the conceptual model of groundwater flowing east to west across the faults. However, specifically how these data support this conclusion is not presented. Sandia should revise the 1995 SWHC Report to include additional discussion on this issue.
Response	***Section 3.2.4.3.3 has been revised to provide additional discussion related to conservative species water chemistry and groundwater flow across the Tijeras fault.***	

Response to EPA's draft "EPA Comments on the SNL 1995 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Section or Subject	Comment
4.	3.2.4.3.5 Groundwater geochemistry	The 1995 SWHC Report presents a brief summary of conclusions presented in Attachment 2, but the discussion is disjointed, presenting only localized information without integrating this information on a site-wide basis. While it is understood that data distribution and the purpose of data collection activities will impact how extensive any interpretation based upon geochemical data can be, the SWHC Report should be revised to include a more comprehensive assessment of site groundwater geochemical conditions, or to specify the data limitations that result in the somewhat disjointed presentation within the 1995 SWHC Report.
Response	***Section 3.2.4.3.5 has been revised to improve its organization and explicitly identify data limitations.***	

Comment Number	Section or Subject	Comment
5.	4.2.1 Integrated Hydrogeologic Conceptual Model	The hydrogeologic conceptual model presented in this section includes three Hydrogeologic Regions, the development of which is based on information provided in the Geologic Conceptual Model, Attachment 1. While is it understood that the hydrogeologic conceptual model represents a refinement of the model presented in Attachment 1 and will not, therefore, include all of the same interpretations, it is not clear that some of the issues raised in Attachment 1 were considered when developing the hydrogeologic model presented in the SWHC Report. These topics include but are not limited to: • Hydrologic flow paths in alluvium relative to incised bedrock channels; • Preferential fracture patterns within bedrock relative to fluid flow; • The impact of paleotopographic features on fluid flow; and • The impact of detailed facies variation in Santa Fe Group lithofacies. Sandia should revise the 1995 SWHC Report, as applicable, to ensure these issues are considered within the hydrogeologic conceptual model.
Response	*To address the first three bullets Sandia made revisions to Sections 4.2.2.3.1, 4.2.2.3.2, and 4.2.2.3.1 respectively.* *There were no report revisions made to specifically address the fourth bullet (Santa Fe Group lithofacies variations). The impact of the variations is found throughout the 1995 Annual Report. In Section 4.2.2.1, for example, Hydrologic Region 1 is broken down into subareas based on that concept: Subarea A – Ancestral Rio Grande fluvial facies and Subarea B – Allivial fan facies. Also in Section 3.2.4.3.3, hydraulic gradient and conductivity data and discussion are grouped by facies: fluvial or alluvial. The impact of the variation did not receive significant discussion in the section and appendix dedicated to groundwater modeling (Section 3.2.5 and Appendix E). However, Section 3.2.5 has been changed, and to replace Appendix E, Attachment 4 was written. As discussed therein, the result of changing an existing model of the Albuquerque basin to include the hydraulic properties and distribution of facies from Section 3, Section 4, and Attachment 1 was an improvement. There was better fit to potentiometric data. Furthermore, particle tracking travel times were lower for particles that had only a short distance in the alluvial deposits before entering the fluvial deposits.*	

Comment Number	Section or Subject	Comment
6.	4.3 Major Conceptual Model Uncertainties	The 1995 SWHC Report includes Tables 4.3-1, 4.3-2 and 4.3-3 which present each of the subareas, associated significant conceptual model uncertainties, and useful additional data. However, it is not clear from these tables whether activities will actually be performed to address these uncertainties, or what schedule these activities will be performed under. Sandia should revise the 1995 SWHC Report to include this information. Also, Sandia indicates that the groundwater model thus far is incapable of predicting head values, although it can predict trends in groundwater elevation. The model and associated parameters should be examined to assess how parameter selection should be modified to address this situation.
Response	***We have now revised the 1995 Annual Report as follows:*** ***(a) Placed an "*" at the end of the captions of Tables 4.3-1, 4.3-2, and 4.3-3, and added the following footnote at the base of each table:*** * The SWHC Project has no plans to collect additional data or to reduce the uncertainties identified in this table. ***(b) Added the final closing paragraphs to Section 4.3, following Table 4.3-3:*** The objective of the SWHC Project was to determine the generalized, overall regional framework of geology, hydrology, and hydrogeology which together determine the regional flow patterns of water and, by extension, flow patterns of contaminants that may be transported by that water. This report meets that objective and completes the SWHC Project. No additional field work or data analysis, including those described as providing "useful additional data" in Tables 4.3-1 and 4.3-3, has been planned for the SWHC Project. SNL/NM task leaders and regulators for individual sites may make determinations on the need to collect any "useful additional data" which are deemed necessary to complete a site-specific evaluation. In addition, Section 3.2.5 and Attachment 4 present updated numerical model calibration issues.	

Response to EPA's draft "EPA Comments on the SNL 1995 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Section or Subject	Comment
APPENDIX E: SNL/KAFB Groundwater Model		
7.	E.3 Conceptual Model and Sandia National Laboratories (SNL) / Kirtland Air Force Base (KAFB) Flow Model.	The SNL/KAFB model covers Hydrogeologic Region 1 (HR-1) but currently does not cover Hydrogeologic Regions 2 & 3 (HR-2 & HR-3); the text states that these regions may be incorporated into the SNL/KAFB model. However, no discussion has been provided to indicate the conditions under which HR-2 and HR-3 will be incorporated into the model. Sandia should revise the appendix to specifically state whether these hydrogeologic regions will be incorporated into the model. If these regions are not to be incorporated into the model, Sandia should include a discussion of the impact of such a decision on evaluating the impact of contaminant releases in these areas.
Response	***Section 3.2.5 was updated and Attachment 4 was added to replace Appendix E. In the discussion in the new text, it is made clear that the modeling is limited to HR-1. Due to high variability in hydrogeologic parameters, the Site-Wide Hydrogeologic Characteriza-tion Project did not perform modeling for HR-2 and HR-3. Should groundwater contamination from sites in HR-2 or HR-3 and potential connection to HR-1 become an issue, it may become important to determine if the SNL/KAFB model should be used or expanded. In this situation, MODPATH, for example, might be run from a cell on the eastern boundary of the SNL/KAFB model. See also the response to 1995 Annual Report General Comment #1.***	

Comment Number	Section or Subject	Comment
8.	E.3 Conceptual Model for SNL/KAFB Flow Model	One of the criteria established in Section E.2.1 for selecting the computer code was the capability to simulate the presence of the perched aquifer system underlying the Tijeras Arroyo and Technical Area II (TA-II). However, it is not clear from the description of the model if this feature is actually included in the current modeling effort. Discussion of the baseline calibration results presented Section E.4.3 indicates that water levels from the KAFB-600 series were not used in the calibration. Since these wells are in the area of the perched aquifer system, their exclusion from the calibration process appears to indicate that perched aquifer system has not been included in the model. Sandia should revise the Appendix to indicate if the perched aquifer system is included in the model. If so, Sandia should provide additional discussion indicating how this feature is being incorporated into the model. If this feature is not explicitly included in the model, Sandia should provide a discussion of the potential impact on the groundwater model, including the prediction of contaminant migration patterns from this area.
Response	***The perched aquifer system is not included in the model. The effect of omitting the perched region is to introduce uncertainty from leakage (recharge) from the perched system to the regional flow system. Section 3.2.5 was revised to indicate that the perched aquifer system is not included in the model. Attachment 4 was written to replace Appendix E and likewise makes the distinction that the model is for the regional aquifer only.***	

Comment Number	Section or Subject	Comment
9.	E.3.2 Description and Evaluation of Boundary Conditions	The Appendix indicates that a no-flow boundary is specified on the east of the model along the Tijeras fault. The Appendix further states that "shallow inflow to HR-1 from HR-2 and HR-3 is distributed to the uppermost active layer in the SNL/KAFB model area as mountain front and/or tributary recharge along the Tijeras fault and the reach of the Tijeras Arroyo using the MODFLOW Recharge Package (pg. E-5)." This approach to modeling the eastern boundary of the model area does not appear to conform with the conceptual model developed for SNL/KAFB area. Flow across the faults has been postulated and certainly such flow would occur at depths greater than the top 20 feet covered by the uppermost active layer in the SNL/KAFB model. Such a boundary condition will likely create strong vertically downward gradients that may not be representative of actual site conditions. Sandia should revise the Appendix to discuss the potential impact of such a boundary condition and to indicate whether this boundary condition will remain unchanged in the recalibrated model.
Response	*The eastern boundary configuration remained unchanged during model calibration. However, a sensitivity analysis was done where a portion of the boundary was converted to specified flow with the flow distributed across the upper 5 model layers. Only the area near the Chemical Waste Landfill (CWL) was converted since it is an area where high hydraulic gradients exist; it is very close to the eastern boundary; and potentiomentric data is available over 3 of the model layers that can be used to assess the impact of the change. The recharge volumetric flow rate was calculated from the recharge rate and grid block areas where recharge was applied, and distributed uniformly over the upper 5 model layers. This recharge distribution resulted in the residual sum of squares being decreased by 5%, mainly due to improvement in matching potentials near the CWL. This amount of variation was judged to be insignificant given the scale of the problem, the project objectives, and the overall uncertainty in facies distribution and associated hydraulic parameters. That is to say, away from the boundary the effect of using the recharge package instead of distributing the flow vertically is minimal.*	

Comment Number	Section or Subject	Comment
10.	General Comment	The Conceptual Geologic Model (CGM) occassionally presents broad conclusions that are unspecific, disjointed or confusing, and that lead to additional questions. For example, on page 2-27, the CGM states that the McCormick Ranch Graben may influence groundwater flow, but presents two opposing interpretations as to how this flow would be impacted by the presence of faults. Also, on page 2-31, the CGM states that because gravel beds occur on the north and south wall of Tijeras Arroyo, the 'gravel beds are continuous over distances greater than 1 mi', but this conclusion is not necessarily supported by the previous statement without further discussion. While these sort of conflicts or tenuous interpretations are generally not reflected in the SWHC Report Hydrogeologic Conceptual Model, future refinement of the CGM could be warranted should new site-specific information lead to more definitive technical conclusions.
Response	**10. Re: General Comment, Attachment 1; subcomments referred to here as "10a" and "10b."** **10a. Re: McCormick Ranch graben and effect on groundwater flow**, page 2-27, 2nd paragraph. **Reply.** **Re-word the second paragraph on page 2-27, beginning "The McCormick Ranch Graben ...", as follows (note that "graben" is not capitalized):** ***The faults bounding the McCormick Ranch graben may influence groundwater movement as either barriers to or conduits for groundwater flow. The faults could be cemented with $CaCO_3$ and/or filled with crushed material. These conditions could impede westward movement of groundwater and allow drawdown of the groundwater trough to the east. Alternatively, but less likely, the faults could be zones of high permeability due to internal fracturing and could provide conduits for groundwater flow.*** **10b. Re: Page 2-31, second full paragraph, correlation of gravel beds from north to south arroyo walls.** **Reply. It is acknowledged that correlations of gravel beds across Tijeras Arroyo are tenuous. The entire paragraph will be deleted.**	

Comment Number	Section or Subject	Comment
11.	2.1.1.2 Description of surfacial mapping units	On page 2-9, Attachment 1 indicates that the age of soil horizons provides 'general infiltration characteristics' of soil horizons. However, it is not clear how the age of the soil horizon is directly related to it's infiltration capacity, since permeability can be either increased or decreased depending upon the specific soil-development characteristics. Sandia should revise the attachment to address this.
Response	**11. Re: Attachment 1, Section 2.1.1.2, description of surficial mapping units.** **Reply. The second sentence of the second paragraph on page 2-9 has been deleted and the following text inserted at that position:** ***This modifier provides an indication of the relative infiltration capacity of the surficial deposit. Infiltration capacities of most local soils are inversely proportional to the length of time during which the soil horizon was stabilized a few feet below the surface and subjected to the influence of climatic conditions (i.e., neither increasingly buried nor eroded away). The local climatic conditions are characterized by a rate of evaporation that greatly exceeds that of precipitation. Calcium salts in solution are transported a few feet into the soil by infiltration of rainwater before the water evaporates. The sources of the $CaCO_3$ are solution in rainwater, and $CaCO_3$ dust washed from the atmosphere or wind-blown onto the surface. The salts precipitate and accumulate as $CaCO_3$ in the soil horizon and develop a whitish, crusty deposit called caliche. Given sufficient time the $CaCO_3$ accumulates to form a caliche with solid, concrete-like, relatively impermeable characteristics. Because the interpretation of the relative age of local soils is based mainly on the amount of caliche developed, it follows that interpreted soil age and anticipated infiltration characteristics are strongly correlated.***	

ATTACHMENT 3: Tijeras Arroyo Infiltration Experiment

Response to EPA's draft "EPA Comments on the SNL 1995 Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Comment Number	Section or Subject	Comment
12.	8.0 Summary and Conclusions	It has been concluded that while numerical simulations of homogeneous material using textbook values of hydraulic properties can misrepresent true conditions, the wetting front advancement computed using hydraulic properties from undisturbed samples was more representative of the observed behavior. However, no direct comparison between predicted and observed water saturations throughout the soil column has been provided. Consequently, it is difficult to determine how effective a tool the numerical model is for predicting subsurface behavior during a large infiltration event. Sandia should revise the Attachment to include a more detailed discussion comparing the simulated results throughout the soil column with actual observed behavior.
Response	*(Response to Comments 12 & 13 appears below Comment 13.)*	
13.		The numerical simulations presented include only homogeneous conditions. However, subsurface heterogeneities may have a significant impact on the vertical migration and horizontal spreading of the infiltrated water. Consequently, to evaluate the potential requirements for reliably modeling infiltration events in the SNL/KAFB area, it would appear necessary to evaluate the need to account for heterogeneous conditions in numerical models used to simulate infiltration events. Such site specific data was apparently collected during the infiltration experiment. Sandia should revise the Attachment to more clearly indicate why it is unnecessary to consider spatial heterogeneities during simulation of infiltration events. Otherwise, Sandia should provide additional numerical simulations to evaluate the potential impact of spatial heterogeneities on model results.
Response	Sandia acknowledges the shortcomings noted by the reviewer regarding the modeling applied to this experiment. Since the application of this experiment to the individual SWMUs at Sandia has been negligible, the Site-Wide Project has no plans to continue modeling for this experiment.	

Response to EPA's draft "Suggested Remaining Activities for the Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Response to EPA's draft "Suggested Remaining Activities for the Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Major Area of Investigation	Setting/Topic	Additional Activities
Vadose Zone	Vadose Zone Hydrology	Sandia indicates that the influence of hydraulic property variability on unsaturated flow and transport, multiphase flow and transport, preferential flow and transport caused by macropore flow and unstable flow, advective and diffusive flow of soil gas, and prediction of groundwater recharge in arid and semiarid climates are areas of current vadose zone research by Gee et al. that might provide methods to understanding vadose zone questions at Sandia National Laboratories/Kirtland Air Force Base (SNL/KAFB). However, it is unclear whether this is being performed as part of specific Site-Wide Hydrogeologic Characterization (SWHC) activities.
Response	***The Site-Wide Hydrogeologic Characterization Project will not be performing more work in this area.***	
Vadose Zone	Tijeras Arroyo Infiltration Experiment	Additional numerical modeling to evaluate the need for incorporating heterogeneous conditions into vadose zone models used to simulate infiltration events is to be performed.
Response	***The Site-Wide Hydrogeologic Characterization Project will not be performing more work in this area.***	
Bedrock Hydraulic Properties	3.2.4.3.2 Hydraulic Properties; Bedrock and alluvial aquifer units in HR-2 and HR-3	The 1995 SWHC Report indicates that little or no hydraulic parameter data have been obtained for the geologic units that comprise the uppermost aquifer in HR-2 and HR-3. If these areas are to be included in modeling as inferred later in the 1995 SWHC Report, it will be necessary to acquire additional hydraulic parameter data from these two areas. In addition, fracture pattern analysis may be required, although Sandia has indicated, on page 3-42 of the 1995 SWHC Report, that this will be conducted on a site-specific basis.
Response	***The Site-Wide Hydrogeologic Characterization Project decided not to model HR-2 and HR-3. The cost to overcome the hydrogeologic variability and build the model was far greater than the needs of ER sites in HR-2 and HR-3 to use the model. The revised report no longer infers that modeling will be performed in HR-2 and HR-3.***	

Response to EPA's draft "Suggested Remaining Activities for the Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Major Area of Investigation	Setting/Topic	Additional Activities
Environmental Site Restoration Activities	Site-specific studies	It is unclear whether site specific SWMU-related ER studies are considered part of the SWHC, although data from these studies will presumably be used to enhance conceptual models in the future. Refer to Table 1.3-2.
Response	*SWMU-related studies are not part of the Site-Wide Hydrogeologic Characterization Project. Table 1.3-2 was provided to give the reader an idea of how far along the ER Sites were in their process.*	
HR-2 Water Level	Perched aquifer	The 1995 SWHC Report states that KAFB is currently investigating the perched aquifer present in Subarea D-Manzano block, and will report on this investigation in 1996.
Response	*The Site-Wide Hydrogeologic Characterization Project was making the reader aware of other agency progress in that subarea. Due to the lack of SNL/DOE SWMUs in that subarea, the Site-Wide Hydrogeologic Characterization Project will not be following up on studies by other agencies in that subarea.*	
Saturated Zone Hydrology	SNL/KAFB Groundwater Model	Sandia should recalibrate the model and perform sensitivity analysis to evaluate the uncertainty inherent in the calibrated model. Required activities may also include reformulating boundary conditions and extending the model to cover a larger portion of the SNL/AFB area. Depending on the uncertainty inherent in the model, additional groundwater level data may be required. A contaminant transport component should also be added to the model.
Response	*The Site-Wide Hydrogeologic Characterization Project completed the modeling task with sensitivity analysis and calibration. The area was not enlarged nor was contaminant transport modeling performed. However, particle tracking was performed to estimate groundwater travel times. The modeling section was completely revised, and Attachment 4 is provided to replace Appendix E.*	

Response to EPA's draft "Suggested Remaining Activities for the Site-Wide Hydrogeologic Characterization Report" dated 9/17/96

Major Area of Investigation	Setting/Topic	Additional Activities
Groundwater Geochemistry	Geochemical data acquisition	Attachment 1, page 6-1, recommends that additional well installation and hydrologic testing using environmental tracers be performed. However, it is unclear whether these activities will be performed under the SWHC project.
Response	***The Site-Wide Hydrogeologic Characterization Project will not be performing more work in this area.***	

Response to NMED DOE/OB's "Review of the Site-Wide Hydrogeologic Characterization Project Annual Report (Calendar Year 1995)" dated 8/28/96

Response to NMED DOE/OB's "Review of the Site-Wide Hydrogeologic Characterization Project Annual Report (Calendar Year 1995)" dated 8/28/96

DOE OB Technical Comments on 1995 Site-Wide Report 1995 ANNUAL REPORT	
Comment Number	**COMMENTS**
1.	p. 3-49, Table 3.2.4-8 – the method of calculating vertical gradient should be explained (role of screen length, etc)
Response	***The following sentence has been added to the <u>Vertical Groundwater flow</u> section in 3.2.4.3.3.*** ***The vertical gradient at these locations is estimated by dividing the difference in water level between the individual monitoring wells by the vertical distance between the mid-points of the respective well screens.***
2.	p. 4-1, section 4.1 – "infiltration and surface runoff" are listed together; although related in arroyos, they are actually different things and should be treated separately. Also, "infiltration" is listed but "recharge" is not; as both are important, but different, "recharge" should be added.
Response	***The following revision has been made to the list.*** ***Some important hydrologic processes and conditions that are related to contaminant transport include:*** • ***Interception*** • ***Infiltration*** • ***Recharge*** • ***Surface runoff*** • ***Soil-water storage*** • ***Evapotranspiration*** • ***Soil-water potential*** • ***Water flow in the unsaturated zone*** • ***Groundwater flow in the saturated zone***

Comment Number	COMMENTS
3.	p. 4-18, section 4.2.2.3.2 – the possibility that ground water becomes temporarily perched on bedrock in the alluvium should be investigated; Figure 4.1-1 shows the area to be characterized by high infiltration capacity
Response	***The following revision has been made to Section 4.2.2.3.2.*** ***Information gained from streamflow gaging, seismic surveys, and drilling done in Lurance Canyon in 1994 suggests that there is no significant alluvial aquifer along the stream channels upstream of Coyote Springs (SNL/NM 1995). However, the potential for water infiltrating into the canyon alluvium and becoming temporarily perched along the alluvium-bedrock contact exists. To evaluate this potential, the SNL/NM ER Project is developing a field program to install piezometers across this contact in the vicinity of the Burn Site in upper Lurance Canyon.***
4.	p. 4-21, Table 4.3-3 – hydrogeologic uncertainties in Subarea H could be resolved by drilling some wells
Response	***Table 4.3-3 has been revised to include the following "Useful Additional Data" for Subarea H*** ***- Additional bedrock monitoring wells*** ***- Piezometers across the alluvium-bedrock contact***

Comment Number	COMMENTS
5.	p. D-5 – the inclusion of geologic logs or a cross section of the wells tested would be useful
Response	*The following references to geologic logs and cross-sections have been included in Section D.5* *Geologic context of the five wells is provided by cross-section figures in Attachment 1 to this 1995 annual report :* • *TJA-2 is located 15 ft east of the KAFB-0311 well which appears in Figures 3.1-14 and 3.1-20* • *TRN-1 appears schematically in Figure 3.2-3* • *MRN-1 appears in Figures 3.1-17 and 3.1-19* • *PL-2 and PL-3 are located 20 ft and 40 ft northwest, respectively, of PL-1, which appears in Figures 3.1-16 and 3.1-19* *Additionally, LOGGER plots are available for four of the five wells, TJA-1, TRN-1, MRN-1, and PL-2, in Appendix 2 of Attachment 1.*
6.	p. D-7, section D.5.3 – SNL attributes flattening of the drawdown curve to the cone of depression intersecting the Madera Limestone (Group). As this underlies the Abo Formation, in which the well is screened, an explanation is needed (folding or faulting would be required to juxtapose the Abo and Madera); a cross section/additional text would help.
Response	*Page D-7 has been revised to delete the sentence attributing the flattening of the drawdown curve to the cone of depression intersecting the Madera limestone*

Comment Number	COMMENTS
7.	Figure D-13 – the placement of the straight-line fit looks too low, based on the end points indicated
Response	*Section D.5.4 and Figure D-13 were revised to reflect two different straight-line fits* ***Hydraulic conductivities were determined using the Cooper-Jacobs (1946) method (Figure D-13). Both early-time and late-time drawdown data were analyzed. The early-time drawdown data (3 to 60 minutes, straight-line fit #2) resulted in a steeper slope and yielded a hydraulic conductivity of 26 ft/day. The late-time data (20 to 3000 minutes, straight-line fit #1) yielded a higher hydraulic conductivity of 47 ft/day.***
8.	p. D-8, section D.5.5.2 – SNL reports that water levels in PL-2 did not respond to pumping of PL-3; this is not clear from Figure D-18.
Response	*Section D.5.5.2 (including new Figure D-19) was revised to clarify the water-level changes in well PL-2 during the PL-3 aquifer test* ***Note that the scales used for the two wells differ in Figure D-18. The apparent parallel decline of approximately 0.05 ft in well PL-2 during the 22 ft decline in well PL-3 is believed to be related to barometric pressure changes during or near the same period. The barometric pressure and its impact on the PL-2 water level data is shown on Figure D-19. Together D-18 and D-19 show:*** ***1. The water levels in well PL-2 decline with an increase in barometric pressure,*** ***2. The water level decline in well PL-2 began before pumping started, and*** ***3. The water level in well PL-2 begins to rise before pumping ceases.***
9.	p. D-9, section D.7 – well construction diagrams would help
Response	***New Figure D-21 - Well construction diagram for TA2-NW1-595, has been added to the report***
10.	Figure D-21 – it is not clear for which day in Figure D-20 the data are plotted
Response	**The new figure title is "Cooper Jacob (1946) Analysis of the TA-2-NW-1-595 Drawdown Data for the Period June 2-14, 1995". Also note that the figure number is now numbered D-23.**

Response to NMED DOE/OB's "Review of the Site-Wide Hydrogeologic Characterization Project Annual Report (Calendar Year 1995)" dated 8/28/96

<table>
<tr><th colspan="2">GEOLOGICAL STUDY (GRAM)</th></tr>
<tr><th colspan="2">COMMENTS</th></tr>
<tr><td colspan="2">The geologic study by Gram, Inc., is an excellent compilation and synthesis of existing information. It provides the final component for the conceptual hydrogeologic model of Kirtland Air Force Base. DOE OB suggests that NMED's wells at ITRI should have been used as they provide useful lithologic and water-level data. We archived drill cuttings with the New Mexico Bureau of Mines and Mineral Resources so others could use them and made Gram personnel aware of this.</td></tr>
<tr><td>Response</td><td>Although GRAM did not perform a detailed study of the cuttings mentioned, the following was done.

Prior to construction of Plates XIII (subsurface bedrock geology) and XV (subsurface bedrock elevation map), detailed, 1:3000 scale work-maps were constructed and the interpretations incorporated into the final 1:12,000 plates. There are 34 data points in the ITRI area and 33 were used for maps. The NMED IP-5 well, the 34th data point, was the only one not incorporated, but its bedrock elevation value of +5516' has no significant effect on the interpretation shown by Plate XV.

Bottom-hole cuttings from NMED-1 well were examined in the field. Bill McDonald provided identification and depth of the bedrock formations encountered in the subsurface in the five holes drilled by NMED on Isleta Pueblo.

There are no report changes resulting from this comment.</td></tr>
</table>

HYDROCHEMICAL STUDY (RUST GEOTECH)	
Comment Number	**COMMENTS**
1.	p. 2-6, Table 2-4 – the calculations made by PHREEQE should be discussed further (for ex, give the definition/equation for ionic strength and the molalities used for calculating it)
Response	*1. The following paragraph will be added to the bottom of page 2-4:* ***Ionic strength values shown in Table 2-4 are those computed by PHREEQE using its extended Debye-Huckle theory and the MRD. Additional information about these calculations and the software can be obtained from the USGS through the internet (http://h2o.usgs.gov/software/).***
2.	p. 4-2, Figure 4-1 – as shown in the Gram report (Figure 1.4-4), Upper Permian strata also occur on KAFB
Response	***2. The Gram report was completed a few months after the hydrochemical study was; therefore, an older version of the figure was used in the hydrochemical study.***
3.	Interestingly, both the study by Rust and the DOE OB (Moats and Winn, 1995) conclude mixing of shallow and deep water is responsible for the hydrochemistries observed. The main difference is the degree of mixing invoked.
Response	***3. Comment acknowledged. There are no report changes resulting from this comment.***

TIJERAS ARROYO INFILTRATION EXPERIMENT	
COMMENT	
The project had the worthwhile objective of characterizing the response of the vadose zone to medium-sized leaks and spills across the facility and produced some interesting results. However, there seems to be little application of the results to this issue or discussion of the implications of the results.	
Response	***The principle conclusion reached was that infiltrating water spread somewhat faster laterally than downward. This conclusion may be only valid for sites with similar layering and similar leaks or spills. A site owner would determine if the results of this study should be applied their particular situation.*** ***There are no report changes resulting from this comment.***

DOE OB EDITORIAL Comments	
1995 ANNUAL REPORT	
Comment Number	**COMMENTS**
1.	The terms "Paleogene" and "Neogene" are used in the text (3.1.2.4 and 3.1.2.5) and they are defined in the glossary, however, they are not shown on the geologic time scale as indicated there ("Tertiary" is used instead).
Response	***Glossary and text have been revised to delete the usage of Paleogene and Neogene. The terms "lower Tertiary" and "upper Tertiary" have been substituted for Paleogene and Neogene, respectively. In addition Figure 3.1.2-1 has been revised.***
2.	p. 2-6 – in the reference to McDonald, 1994, the address should be Albuquerque not Los Lunas
Response	***The McDonald reference has been corrected***

Response to NMED DOE/OB's "Review of the Site-Wide Hydrogeologic Characterization Project Annual Report (Calendar Year 1995)" dated 8/28/96

Comment Number	COMMENTS
3.	p. 3-2, section 3.1.2.4 – it is units of Paleogene age that are not found, not outcrops of Paleogene age
Response	***Section 3.1.2.4 was renamed Lower Tertiary strata per Editorial Comment #1 above and rewritten.***
4.	Figure 3.2.4-5 – streamlines for the fine-grained and ARG facies cannot be distinguished in black and white versions; different styles of lines are needed
Response	***Figure 3.2.4-5 has been revised.***
5.	p. 3-54, section 3.2.4.3.5 – although "geochemistry" technically includes natural water, "hydrochemistry" is the more usual term (and is less cumbersome than "ground-water geochemistry")
Response	***Section 3.2.4.3.5 has been revised to change "groundwater geochemistry" to "hydrogeochemistry".***
6.	p. 4-23 – the reference listed as cited by Lull (1964) should be Wisler (not Wiseler) and Brater
Response	***The Wisler and Brater 1959 reference in Section 4.1.2.1 (and Section 4 References) has been corrected.***
7.	Figure B-6 – it is difficult to distinguish the curves (plot separately); the meaning of the symbols should be explained
Response	***Figure B-6 has been revised to include a symbol Legend.***
8.	Figure C-3 – the legend entry for well screens is unclear; that in Figure C-4 is better (things like this could be standardized throughout the report)
Response	***The "well screen" symbol in the Legend on Figures C-2, C-3, D-3, D-11, and D-15 has been revised.***

Comment Number	COMMENTS
9.	p. D-5, section D.5.1 – Theis (1935) is not referenced. In the first line after the list, reference is made to assumptions by Theis and Jacob; there is no such reference (there is Theis, 1935, and Cooper and Jacob, 1946).
Response	***Section D.5.1 has been revised and the C.V. Theis (1935) reference (see below) has been added to the appendix references.*** ***Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions of the American Geophysical Union 16th Annual Meeting, pgs 519-524.***
10.	Figure D-16 – the reason for the gaps in the plots is not explained
Response	***Figure D-16 has been revised to explain data gap.***

RUST'S HYDROCHEMICAL STUDY	
Comment Number	**COMMENTS**
1.	p. 2-5, section 2.2; p. 4-24, section 4.6; and Appendix E – the term "lithologic" is more appropriate for the make-up of the saturated medium; Appendix E gives rock types, not mineral content
Response	***1. Sections 2.2, 4.6, and Appendix E have the intent of describing, to the extent possible, the mineralogy that affects the groundwater chemistry. The lithology, in the form of descriptions of sands, gravels, etc. is present because it increases the utility of the mineralogic information or because only lithologic data are available. No report changes result from this comment.***
2.	p. 4-1, section 4.2 (and elsewhere) – since "Rio" is Spanish for river, "Rio Grande River" is redundant
Response	***2. That is true. Revised pages 4-1 and 4-6 are included.***
3.	Appendix C – although the significance of the diameter of the spots on maps is given in the text, it should be repeated in the appendix; the same goes for the meaning of "wells with positive/negative values"
Response	***3. Revised page C-1 was generated to include the following reminder:*** ***Round or square spot sizes are proportional to observed concentrations. Negative values for saturation indices indicate concentrations less than saturation (i.e., mineral dissolution is possible), while positive saturation indices indicate super-saturation (i.e., mineral precipitation is possible). Negative values for isotopic ratios indicate water isotopically lighter than ocean water. Negative values for species concentrations indicate analytical errors and presumably very low concentrations.***

TIJERAS ARROYO INFILTRATION EXPERIMENT	
Comment Number	**COMMENTS**
1.	The parameter represented by the contours in Figures 7.7–7.30 is presumably moisture content, but is not identified as such.
Response	*1. Revised Figures 7.7–7.10, 7.12–7.15, 7.17–7.20, and 7.22–7.30 are included with the added caption:* **Contours are fractional, volumetric water content.**
2.	p. 8-1, Section 8.0 – The last paragraph of the Summary and Conclusions should be proofed (extra word in second sentence, spelling error in third sentence).
Response	*2. Section 8.0 was proofed, revised, and attached to this package. The last paragraph was changed to the following:* *Some conclusions have been reached concerning the vadose zone's response. Neutron data suggest that the lateral movement of the wetted bulb is slightly greater than its downward movement. In addition, the lateral spread of the wetted bulb was more extensive in a coarse-textured layer that is sandwiched between two finer textured layers. Numerical simulations of homogenous soils using textbook values of hydraulic properties can misrepresent true conditions. However, when hydraulic properties from the undisturbed sample were used, the computed wetting front advancement was more similar to the observed wetting front.*

RECOMMENDATIONS FOR FURTHER WORK

COMMENTS

SNL has proposed terminating the Site-Wide Project. If this were done, the facility is probably sufficiently characterized on a regional scale for adequate surveillance and ER activities, especially with the completion in 1995 of Gram's geologic study. However, the DOE OB has initiated an informal joint review with SNL (Sue Collins) of Site-Wide Project results to date to identify any information still needed. In the meantime, the DOE OB recommends several areas for further work on a site-wide scale:

1. Although the 1995 report overcomes most of the deficiencies noted by the DOE OB in previous annual reports, if the project is continued, a few items still deserve attention:
   a) add a schedule of future tasks to annual reports,
   b) give data-quality objectives,
   c) include month/day/year for all observations and
   d) provide borehole-deviation survey data in the ERDMS well-file module.
2. Update the regional water-level map as additional data become available.
3. Maintain and update the well and spring data bases as new wells are completed and additional springs are identified.
4. Provide a mechanism for consolidating and disseminating site-wide hydrogeologic data for KAFB.
5. Integrate the information in Rust's report with that given by Moats and Winn (1995) into a conceptual hydrochemical model.
6. Test and compare infiltration rates in the major geomorphic settings identified in the 1995 Site-Wide study. If simple field methods are employed, more settings can be covered.

Reference Cited – Moats, W. P., and Winn, L., 1995, Background ground-water quality of the Kirtland Air Force Base Area, Bernalillo County, New Mexico: New Mexico Environment Department Report NMED/DOE/AIP-95/4, 78 p.

Response ***The informal joint review mentioned in this comment was concluded in an NMED DOE/OB memo dated 4/7/98 to Beth Oms, re: Review of SNL's Conceptual Model and Numerical Sitewide Hydrogeological Models. No further site-wide work is planned at this time.***

Response to NMED DOE/OB's "Review of SNL's Numerical Sitewide Model" dated 3/11/98

Response to NMED DOE/OB's "Review of SNL's Numerical Sitewide Model" dated 3/11/98

Comment Number	GENERAL COMMENTS
1.	SNL did a good job of explaining most modeling concepts and parameters for any readers who may be unfamiliar with the topic.
Response	*Comment acknowledged.*
2.	There should be a more obvious distinction in the discussions of steady-state and transient phases of the modeling.
Response	*Text added to last paragraph Section 1.3–* ***"Consequently, the groundwater flow model constructed in this analysis was transient (time-varying), and was derived from the model of Kernodle et al. (1995)."***
3.	There seems to be some confusion about the difference between "acquifer" and "water table." For example, on p. 6 in 2.2.2 and p. 8 in 2.3 the regional water table is referred to as the "top of the regional aquifer." The term "aquifer" refers to a geologic material whose saturated portion yields useful quantities of water to wells. Thus, it regers to the entire geologic unit, not just the saturated portion. The top of the staurated portion is the "water table."
Response	***Change to reflect "water table" made in Sections 2.2.2 and 2.3.***
4.	Care should be taken in the use of "verification" and "prediction" in modeling papers. Models are nonunique and achieving an acceptable history-match does not constitute verification. Well-known USGS hydrologists have gone so far as to say that ground-water models cannot be verified (the title of a now classic journal article). This is to say, models can be disproven, but not proven.
Response	***The brief discussion of verification in Section 3.0 follows the accepted usage of the terms "verification" and "prediction." The SWHC model is not verified. A statement is added in Section 5.0 to the paragraph beginning, "The SWHC Project model differs from the ABM in several ways…" to the effect that the model is not verified. The statement is as follows, "Since an independent prediction was not attempted the model is not verified (Anderson and Woessner, 1992)."***

Comment Number	SPECIFIC COMMENTS
1.	The orientation of rows and columns should be clarified. This could be done by labeling them on Figure 3.2 and making some reference to compass directions in addition to or instead of "x/y" in the text (p. 16).
Response	***In the second paragraph of Section 3.3.1 reference is now made to compass directions. On Figure 3.2 New Mexico State Plane easting and northing coordinates are posted around the map border; explicit labeling has been added. The sentence is now, "Block dimensions were uniform in the column, or x direction (east-west orientation), at 650 ft and from 650 ft in the north to 3,700 ft in the south in the row, or y direction (north-south orientation)."***
2.	On p. 31, "artesian" may better convey what is intended than "piezometric" in the discussion of heads.
Response	***Peizometirc rather than artesian is the desired term. The intent was to express the difference between water-table conditions where transmissivity is a function of hydraulic head and confined conditions where it is not.***